The Electroweak, The Strong and the Unknown

Beate Heinemann
University of Liverpool

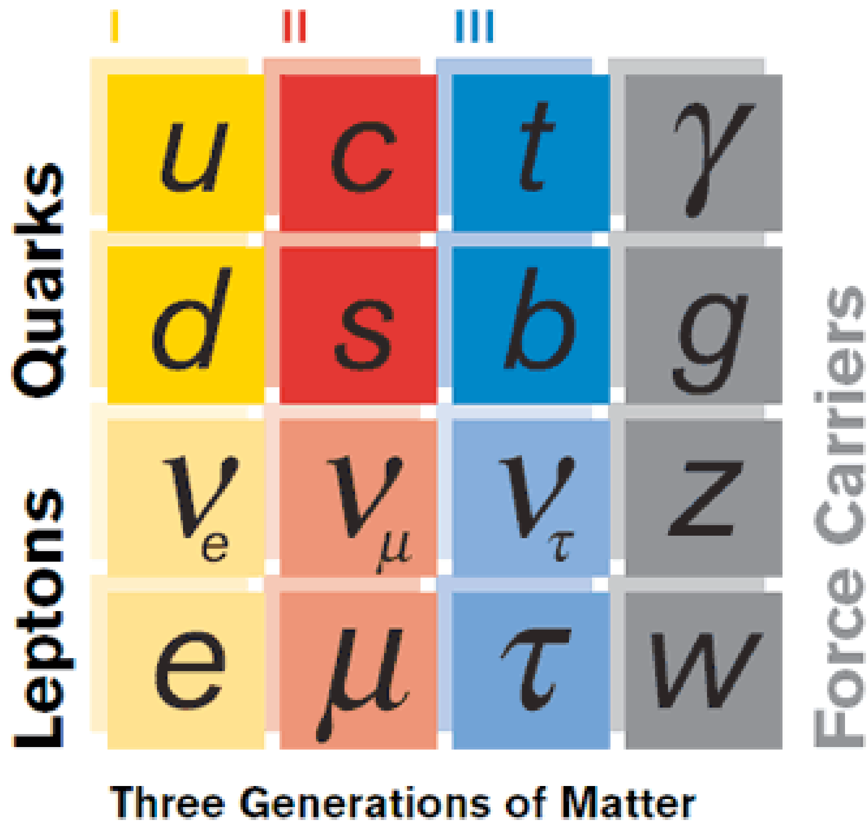
UC Berkeley/LBNL, February 16th 2006

Outline

- Introduction
- The Tools:
  - Present: HERA, Tevatron
  - Future: LHC, ILC
- The Electroweak Force
  - Deep Inelastic Scattering
  - Trilinear Gauge Couplings
- The Strong Force
  - Probing the proton structure
- The Unknown
  - Supersymmetry
- Conclusions

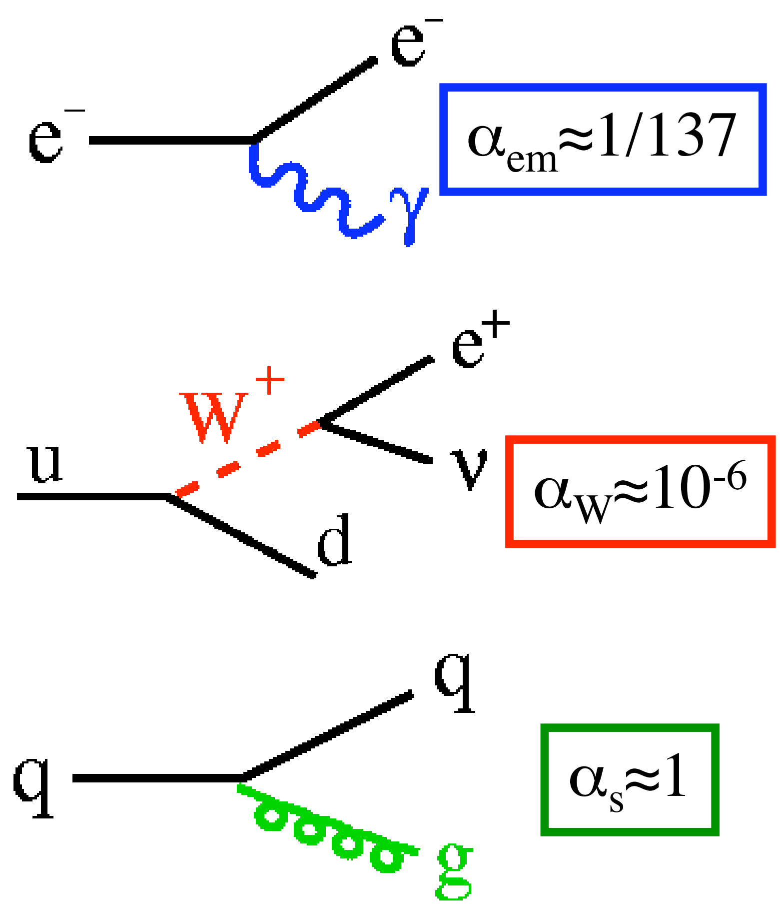
The Standard Model

- Matter is made out of fermions:
  - quarks and leptons
  - 3 generations
- Forces are carried by Bosons:
  - Electroweak: γ,W,Z
  - Strong: gluons
- Higgs boson:
  - Gives mass to particles
  - Not found yet



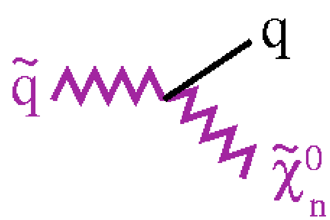
Electroweak And Strong Force

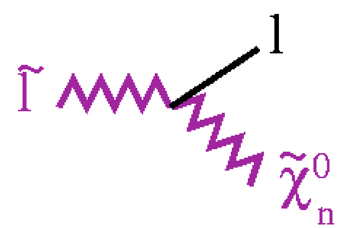
- Quantum field theory is used to describe forces of nature:
  - Unified description of weak and electromagnetic force (Glashow, Salam, Weinberg):
    - Photon
    - W, Z
  - Strong force described by Quantumchromodynamics (QCD)
    - gluons
- Precision measurements test validity of model and calculations

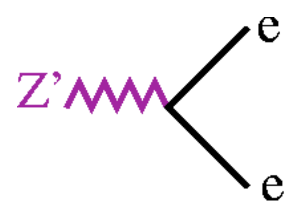


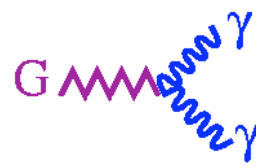
The Unknown

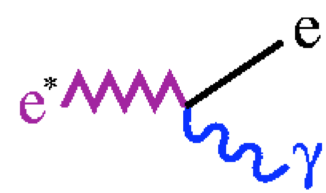
- Many good reasons to believe there is as yet unknown physics beyond the SM:
  - Dark matter + energy, matter/anti-matter asymmetry, neutrino masses/mixing +many more (see later)
- Many possible new particles/theories:
  - Supersymmetry:
    - Many flavours
  - Extra dimensions (G)
  - New gauge groups (Z’, W’,…)
  - New fermions (e*, t’, b’, …)
  - Leptoquarks

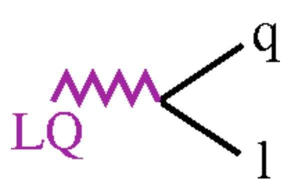




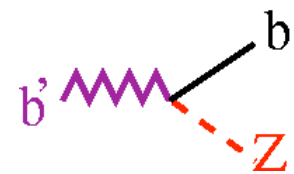








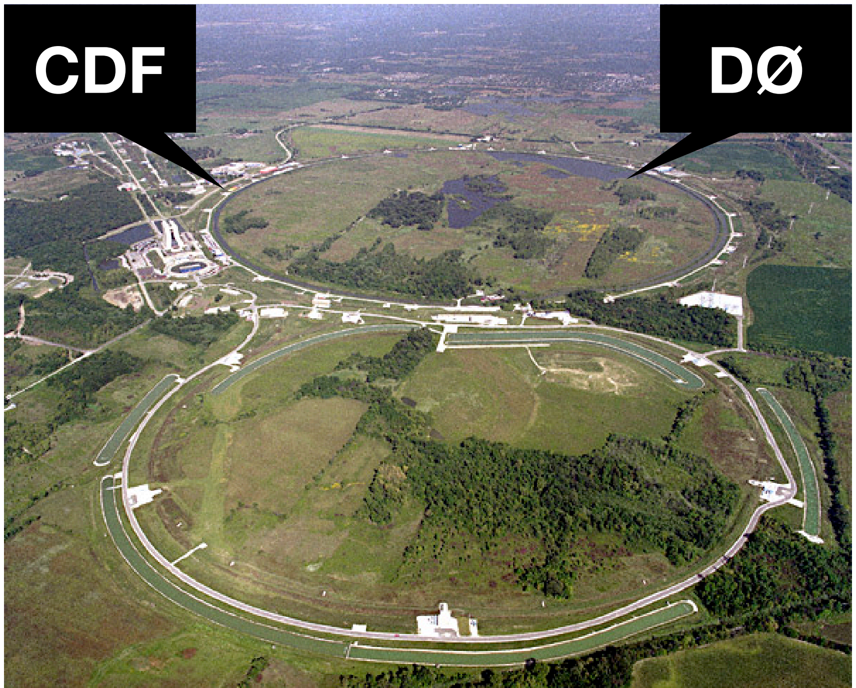
- Can show up!
  - As subtle deviations in precision measurements
  - In direct searches for new particles

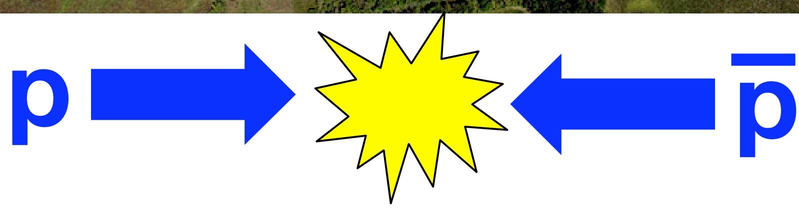


The Tools

Current High Energy Colliders

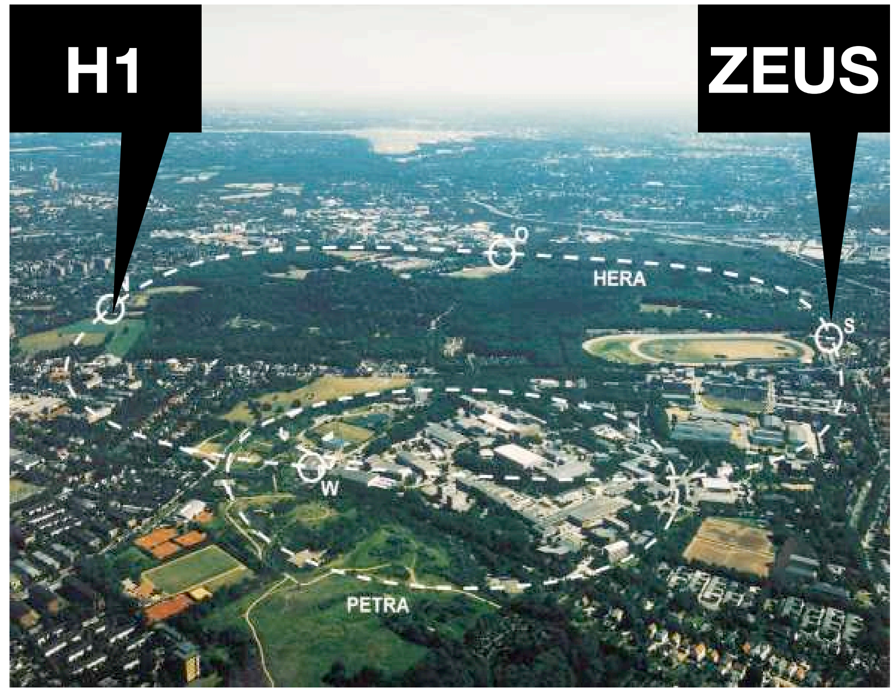
Tevatron

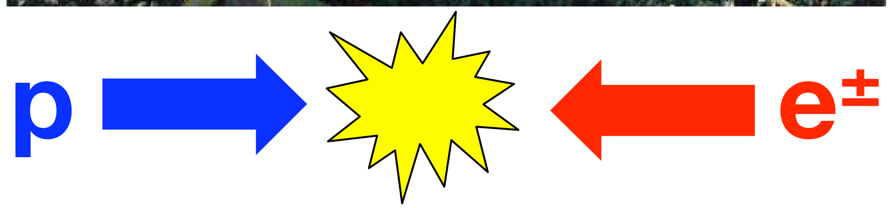




$\sqrt{s}$=1.96 TeV

HERA



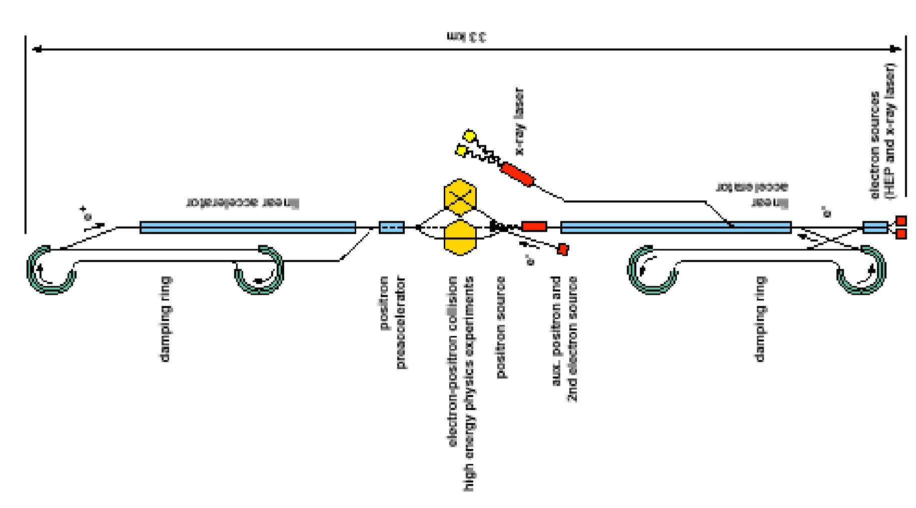


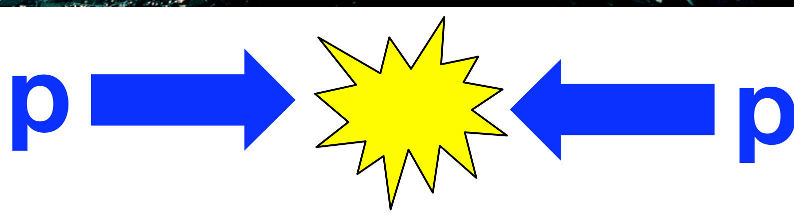
$\sqrt{s}$=0.32 TeV

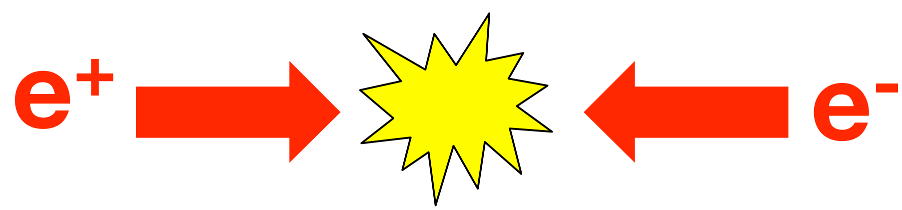
Future High Energy Colliders

LHC (2007–?)

ILC (>2020?)





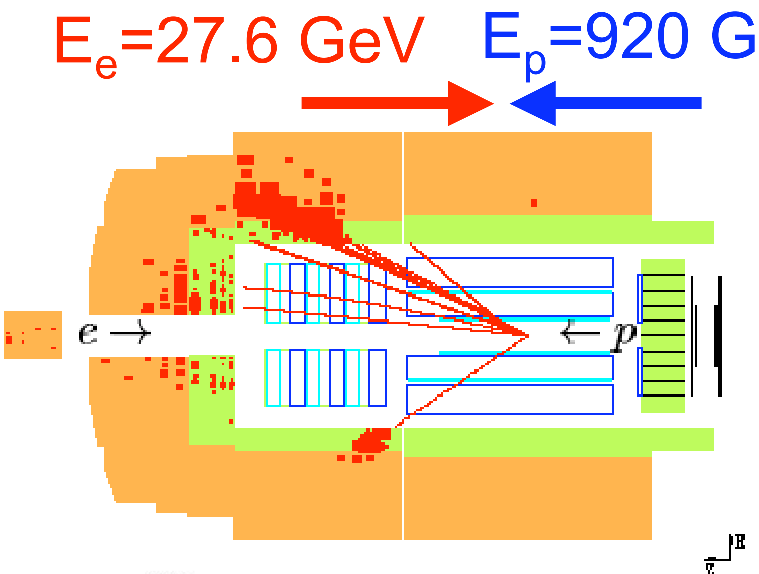


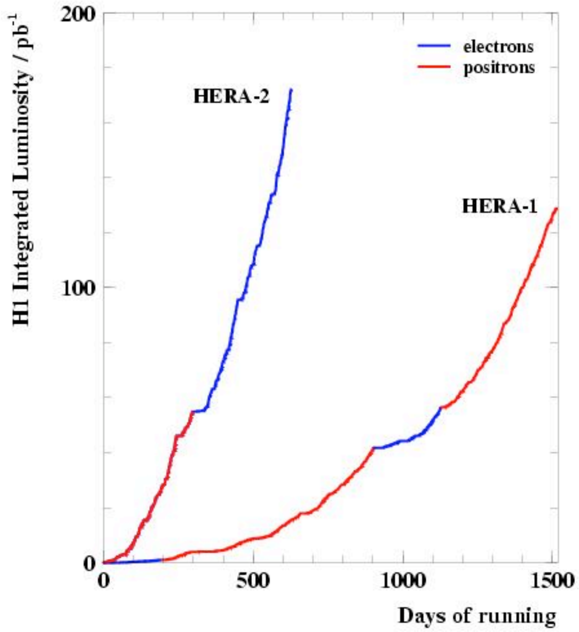
$\sqrt{s}$=14 TeV

$\sqrt{s}$=0.5–1 TeV

H1 AT HERA

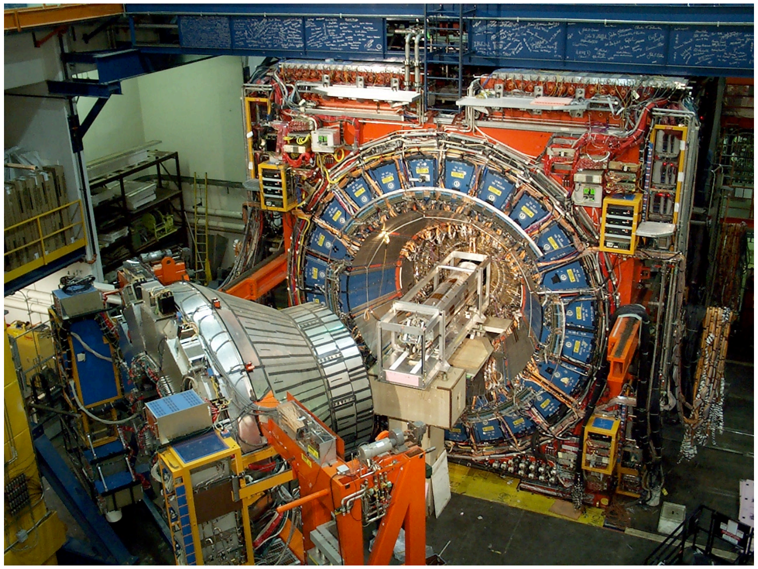
- **Asymmetric detector**
  - **Most particles go forward due to higher proton energy**
- **Luminosity:**
  - **HERA-1 running ended in 2000:**
    - **$\int L dt$ = 130 pb^{-1}**
    - **Results shown here**
  - **HERA-2 run started in 2001:**
    - **$\int L dt$ = 170 pb^{-1}**

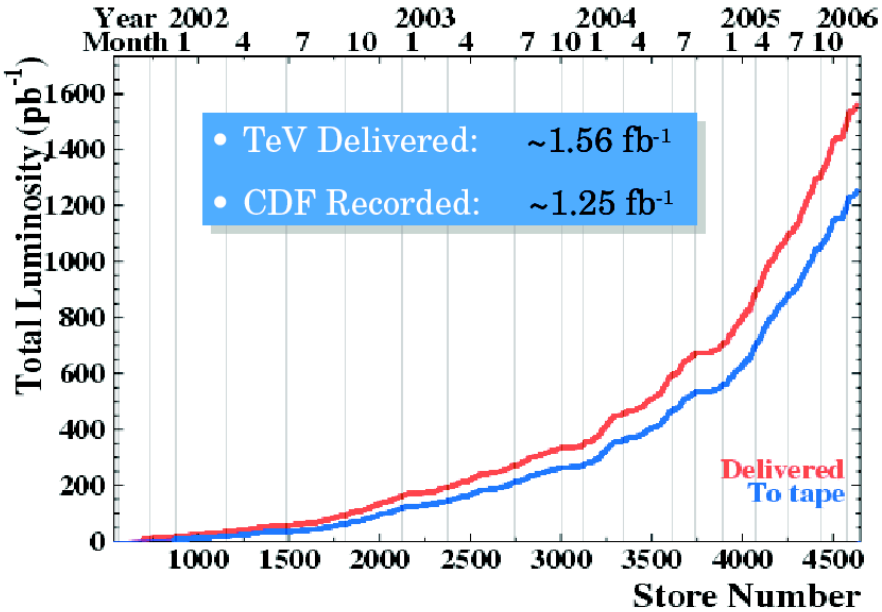




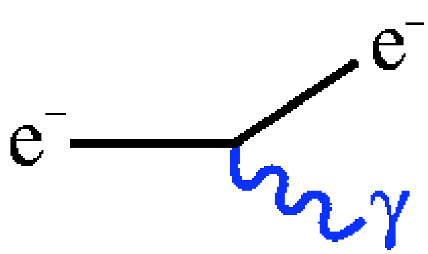
CDF at the Tevatron

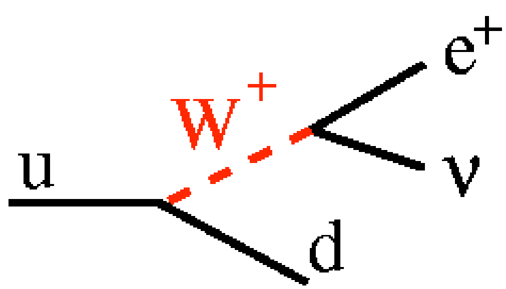
- Multi-purpose detector
  - Excellent tracking
    - Silicon and drift chamber
  - Calorimetry
  - Muon systems
  - Time-of-flight detector
- Luminosity:
  - $\int L dt = 1.25\ fb^{-1}$ recorded





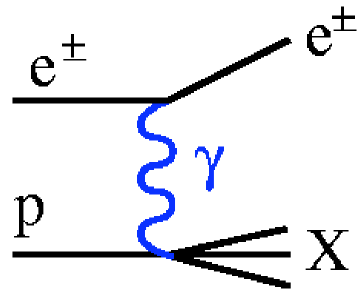
The Electroweak, the Strong and the Unknown

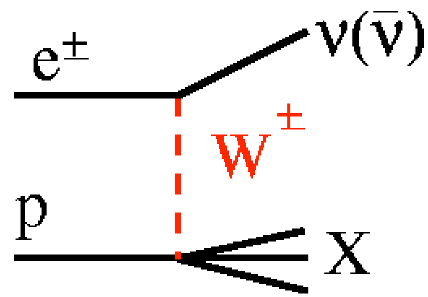




TESTING ELECTROWEAK THEORY

- Strength of electromagnetic and weak forces:
  - Photon exchange:
    - $\sigma \propto \alpha_{em}^2/Q^4 \propto e^4/Q^4$

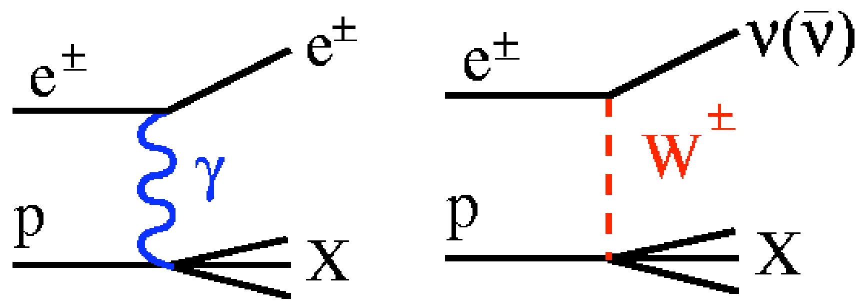




  - W boson exchange:
    - $\sigma \propto G_F^2 M_W^4/(M_W^2+Q^2)^2$ $(G_F/\sqrt{2} = g^2/8M_W^2)$
      - for $Q^2 \approx 0$: $\sigma \propto G_F^2$
      - for $Q^2 \gg M_W^2$: $\sigma \propto G_F^2 M_W^4/Q^4 \propto g^4/Q^4$
    - Weakness at low energy comes from M_W term, not from coupling $g = e/\sin^2\theta_W \approx 4e$

TESTING ELECTROWEAK THEORY

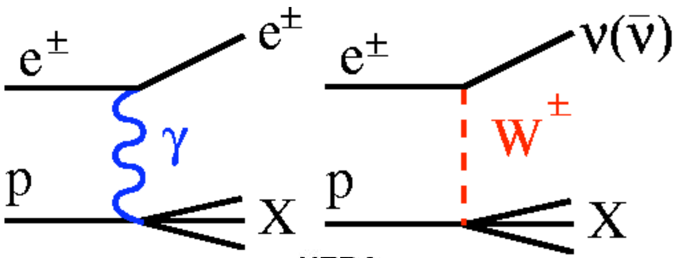
- **Strength of electromagnetic and weak forces:**
  - **Photon exchange:**
    - $\sigma \propto \alpha_{em}^2/Q^4 \propto e^4/Q^4$
  - **W boson exchange:**
    - $\sigma \propto G_F^2 M_W^4/(M_W^2+Q^2)^2$ $(G_F/\sqrt{2} = g^2/8M_W^2)$
      - for $Q^2 \approx 0$: $\sigma \propto G_F^2$
      - for $Q^2 \gg M_W^2$: $\sigma \propto G_F^2 M_W^4/Q^4 \propto g^4/Q^4$
    - **Weakness at low energy comes from M_W term, not from coupling $g = e/\sin^2\theta_W \approx 4e$**

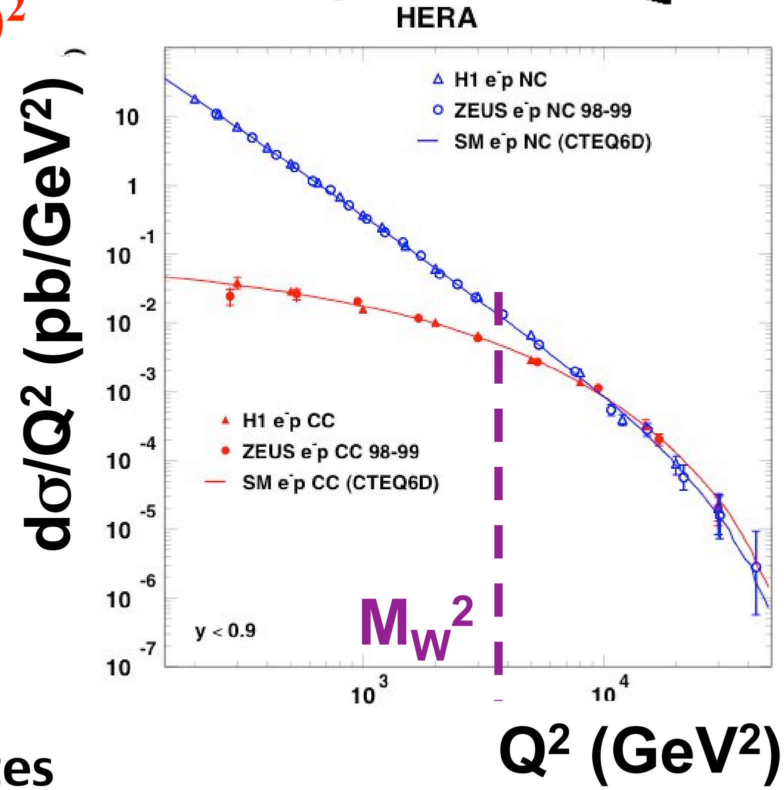


Expect both forces to be similar for $Q^2 > M_W^2$
=> Test in deep inelastic scattering at HERA

Neutral and Charged Current Cross Sections

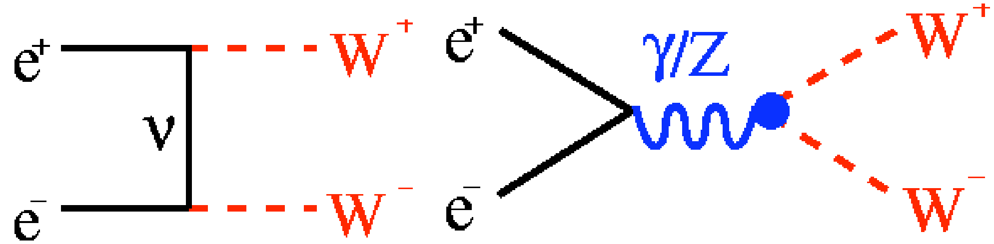
- Processes:
  - Neutral Current (NC): $\propto 1/Q^4$
    - Observe scattered electron
  - Charged Current (CC): $\propto 1/(M_W{}^2+Q^2)^2$
    - Observe missing transverse energy from neutrino
- Electroweak unification seen:
  - At $Q^2 \approx 100$ GeV^2:
    - 3 orders of magnitude different
    - CC cross section nearly independent of Q^2
  - At $Q^2 \approx 10000$ GeV^2:
    - Very similar
    - CC cross section falls as steeply as NC
    - In NC case Z exchange also contributes

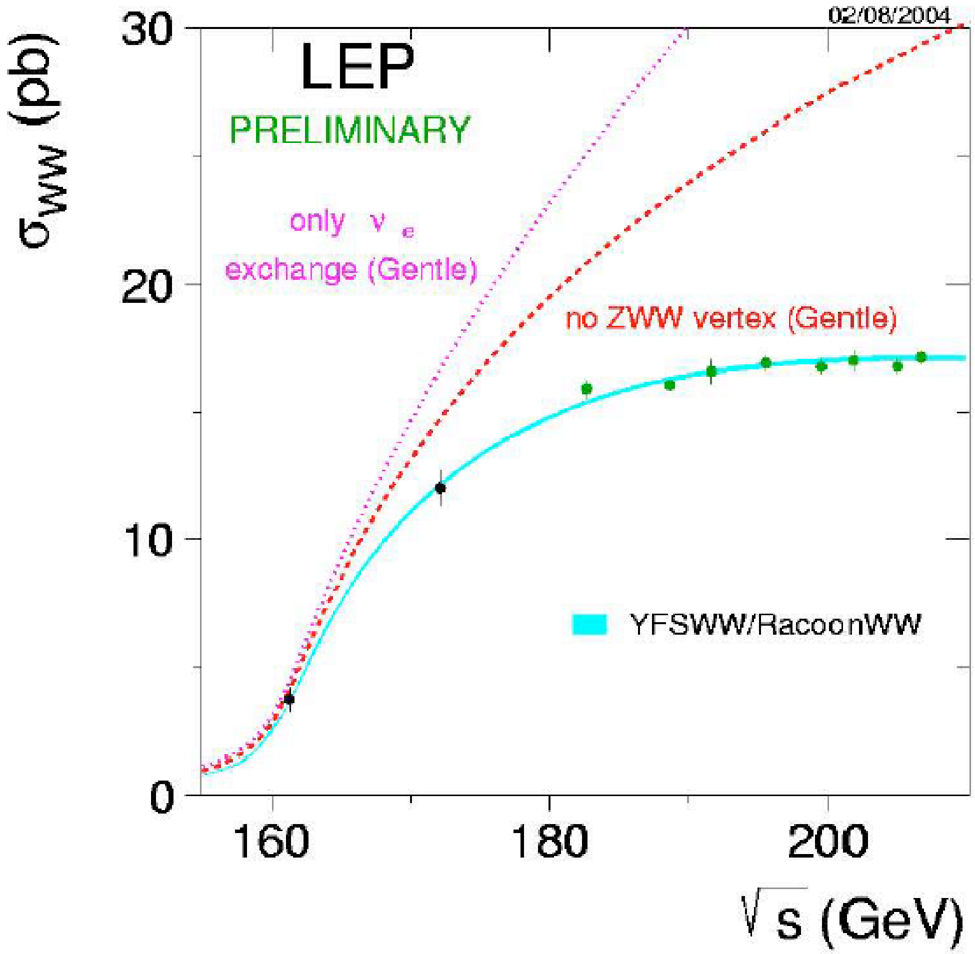




Trilinear Gauge Couplings

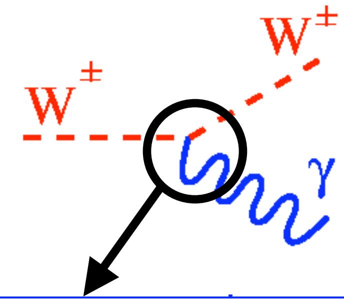
- Group: SU(2)xU(1)
- SU(2) is non-abelian gauge group:
  - Triple and quartic couplings of gauge bosons
  - Strength of couplings precisely predicted
- Probed at LEP2:
  - WW cross section
  - Data disagree with models w/o triple vertex
  - Data agree well with Standard Model prediction





Anomalous Couplings

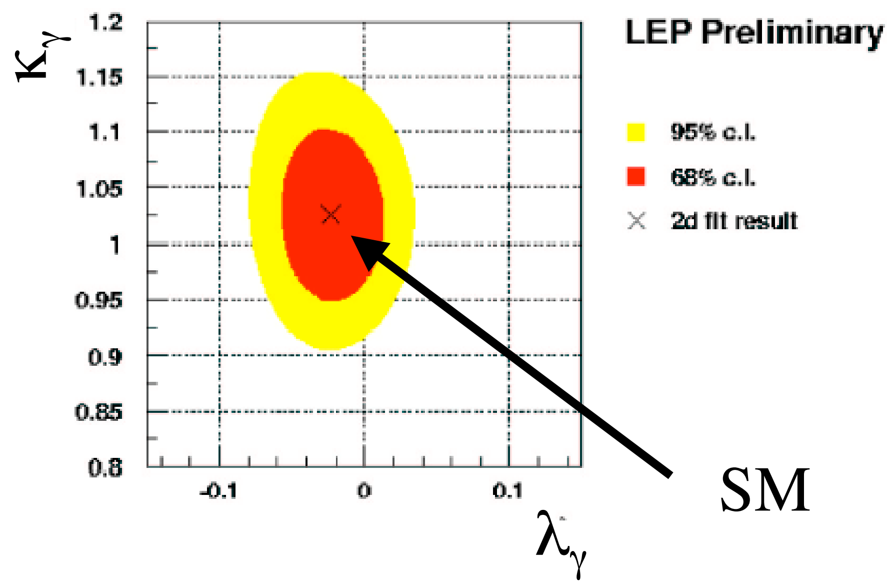
- Most generally
  - 7 WWγ and 7 WWZ couplings
- Impose
  - gauge invariance
  - conservation of C and P
  - Assume $\kappa_\gamma = \kappa_Z$ and $\lambda_\gamma = \lambda_Z$
- Reduce to three independent parameters:
  - $g_1^Z, \kappa_\gamma, \lambda_\gamma$ (= 1, 1, 0 in SM)
  - Related to magnetic dipole moment and electric quadrupole moment of W
- Precise results from LEP2:
  - Agrees with Standard Model
  - Probes couplings at 5–10% level



Anomalous couplings : $\Delta\kappa, \lambda$

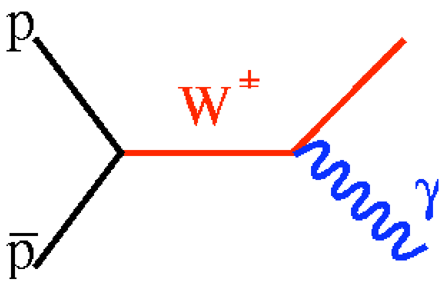
$$\mu_W = e(1+\kappa_\gamma+\lambda_\gamma)/2m_W$$

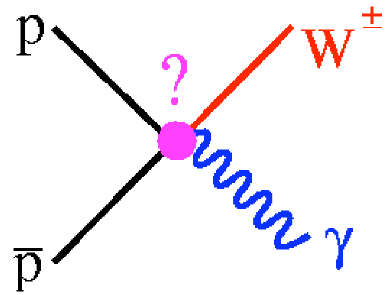
$$q_W = -e(\kappa_\gamma-\lambda_\gamma)/m_W^2$$

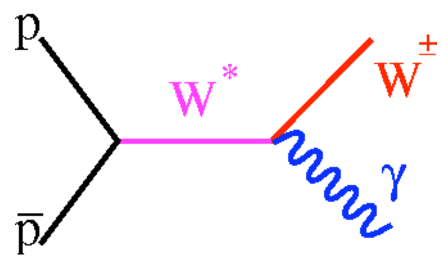


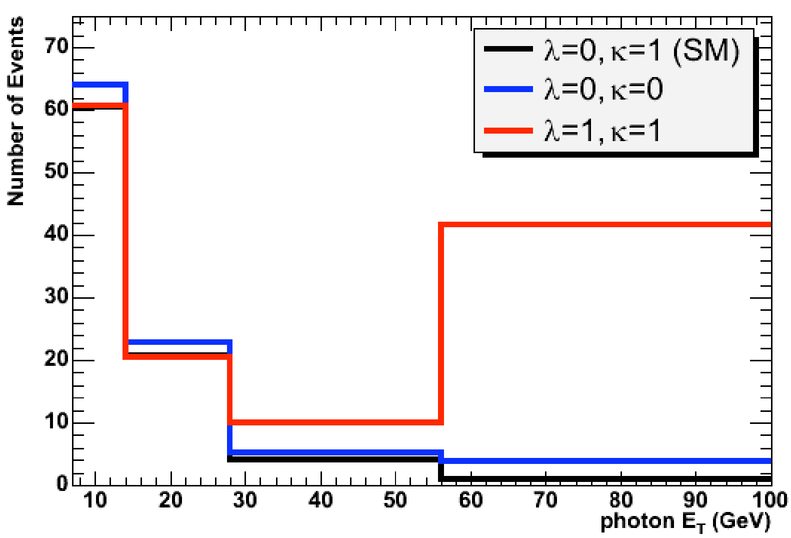
Wγ Production: Tevatron

- **Direct sensitivity to photon:**
  - No assumption on WWZ coupling
- **High energy:**
  - Sensitive to high mass scale physics (e.g. W*)
- **Anomalous couplings increase cross section at high photon E_T**
  - Best sensitivity to λ



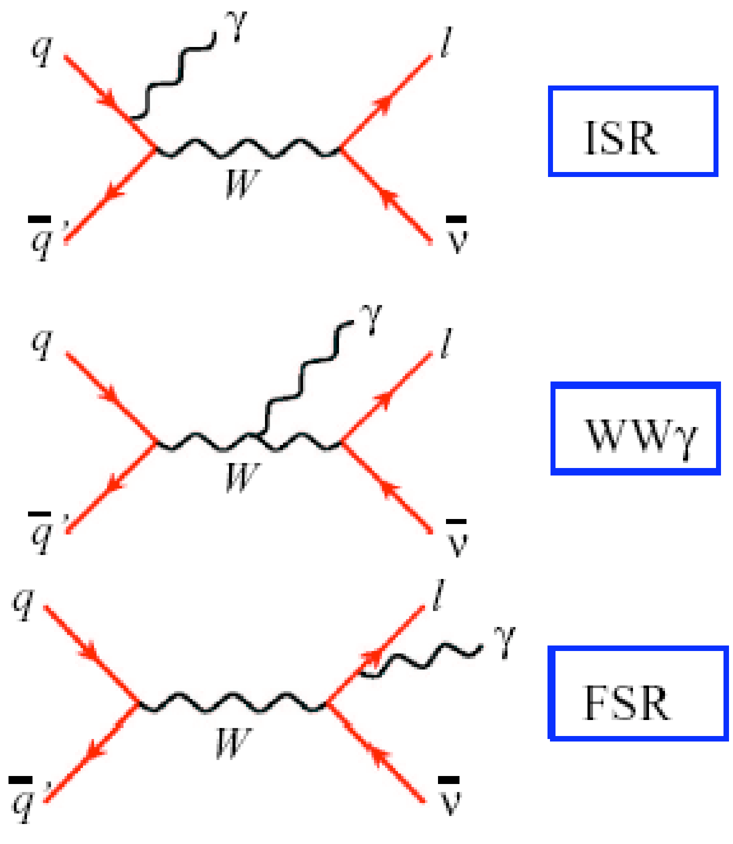




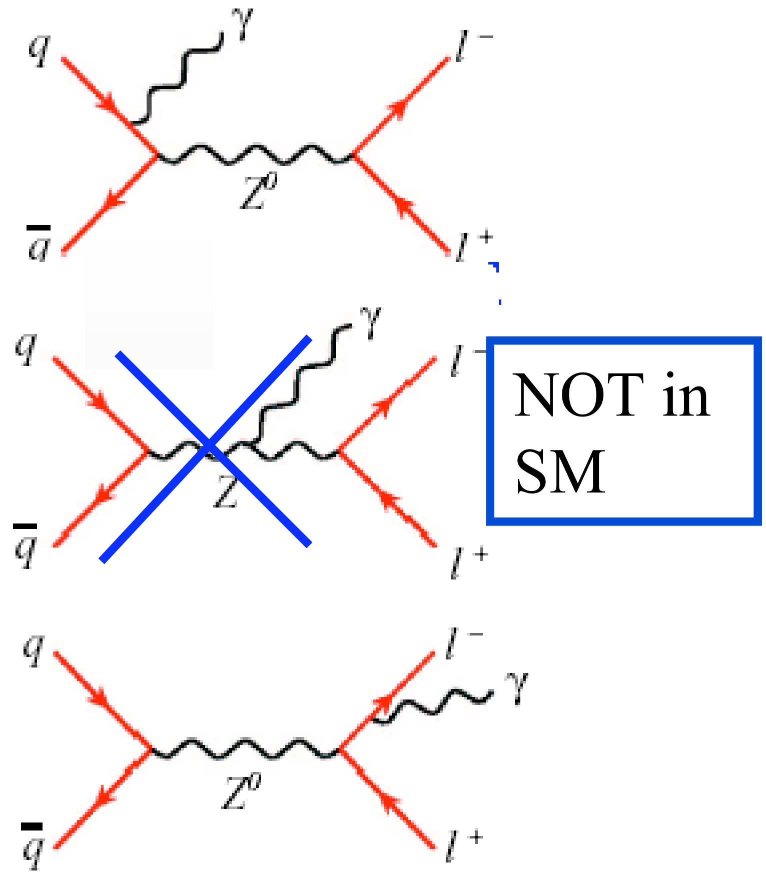


Wγ and Zγ Production

Tree-level diagram of
$\bar{p}p \rightarrow W\gamma \rightarrow l\nu\gamma$



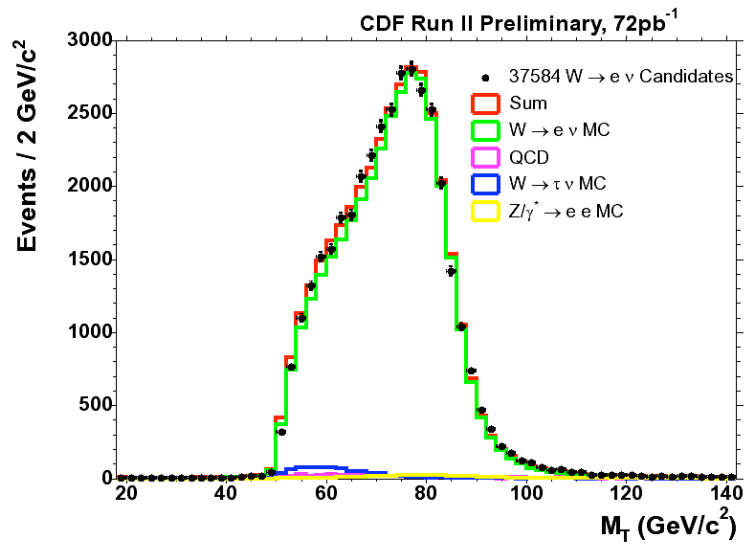
Tree-level diagram of
$\bar{p}p \rightarrow Z\gamma \rightarrow ll\gamma$

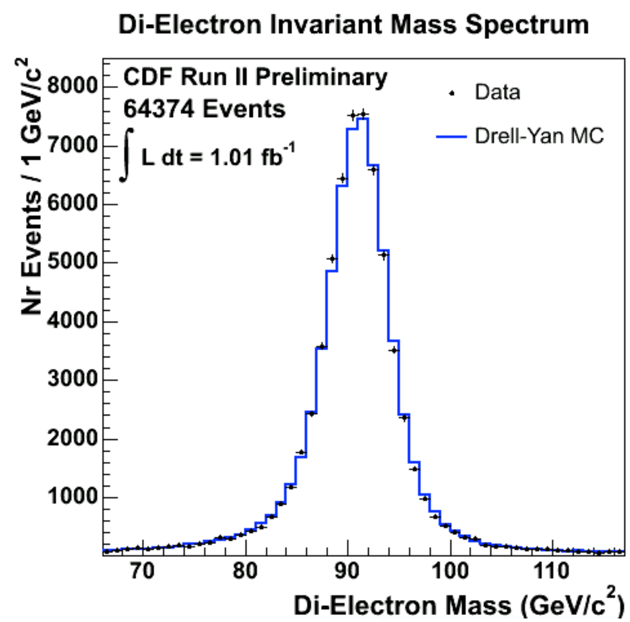


These diagrams interfere and decay products are detected in the detector

EVENT SELECTION

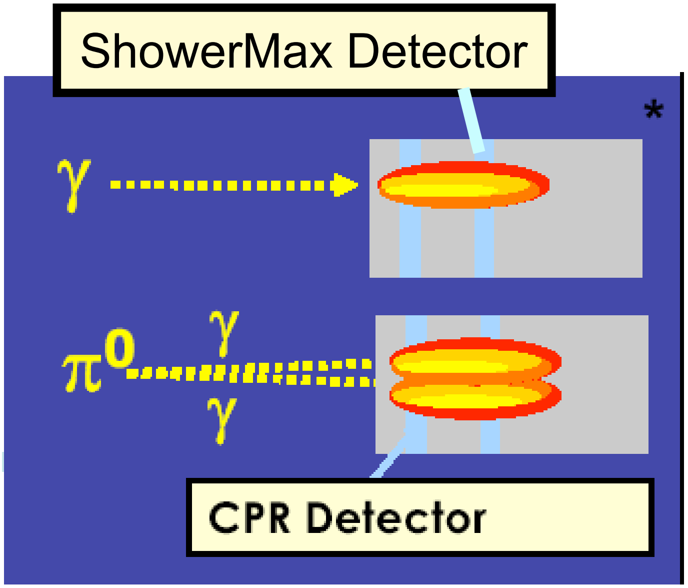
- **W**:
  - Isolated electron or muon
    - p_T>20 GeV
  - Missing transverse energy
    - $\not{E}_T$ >20 GeV
- **Z**:
  - Two isolated electrons or muons:
    - p_T>20 GeV
- **Photon**:
  - Isolated electromagnetic cluster with no track
    - E_T>7 GeV
- **Final states for analysis:**
  - $e\nu\gamma$, $\mu\nu\gamma$ and $ee\gamma$, $\mu\mu\gamma$

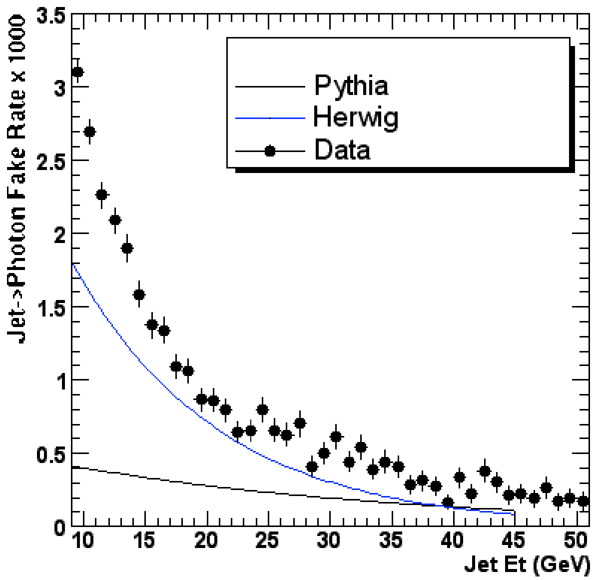




Photon Background

- **Biggest challenge in analysis:**
  - **Background to photons**
  - **Particularly from $\pi^0 \rightarrow \gamma\gamma$**
- **Discriminate on basis of**
  - **Shower shape:**
    - **π^0's are broader**
  - **Conversion probability:**
    - **π^0's have higher probability**
- **Measure rate at which "jets" look like photons**
  - **Subtract prompt photons statistically from jet sample**
  - **Result:**
    - **About 0.3–0.05% depending on photon E_T**





Wγ and Zγ Cross Sections

Wγ

	$e\nu\gamma$	$\mu\nu\gamma$
W+ γ	126.8 ± 5.8	95.2 ± 4.9
W+jet BG	59.5 ± 18.1	27.6 ± 7.5
W+ γ (tau)	1.5 ± 0.2	2.3 ± 0.2
Z+ γ	6.3 ± 0.3	17.4 ± 1.0
Total SM	194.1 ± 19.1	142.4 ± 9.5
data	195	128
σ*BR (pb)	19.4 ± 3.6	16.3 ± 2.9

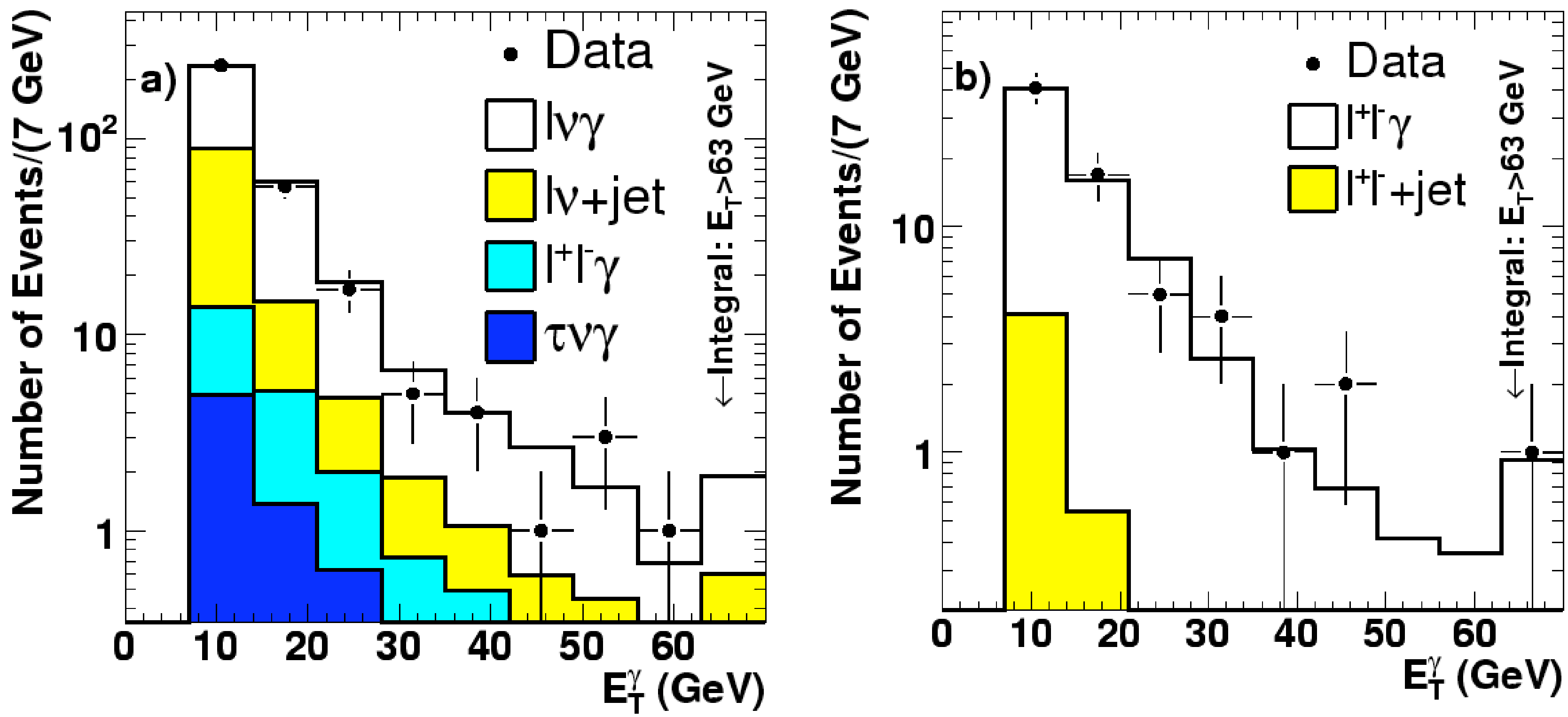
Zγ

	$ee\gamma$	$\mu\mu\gamma$
Z+γ	31.3 ± 1.6	33.6 ± 1.5
Z+jet BG	2.8 ± 0.9	2.1 ± 0.7
Total SM	34.1 ± 1.8	35.7 ± 1.6
data	36	35
σ*BR (pb)	4.8 ± 0.9	4.4 ± 0.8

σ* BR ($W\rightarrow\ell\nu$)=18.1 ± 3.1 pb
Theory: 19.3± 1.4 pb

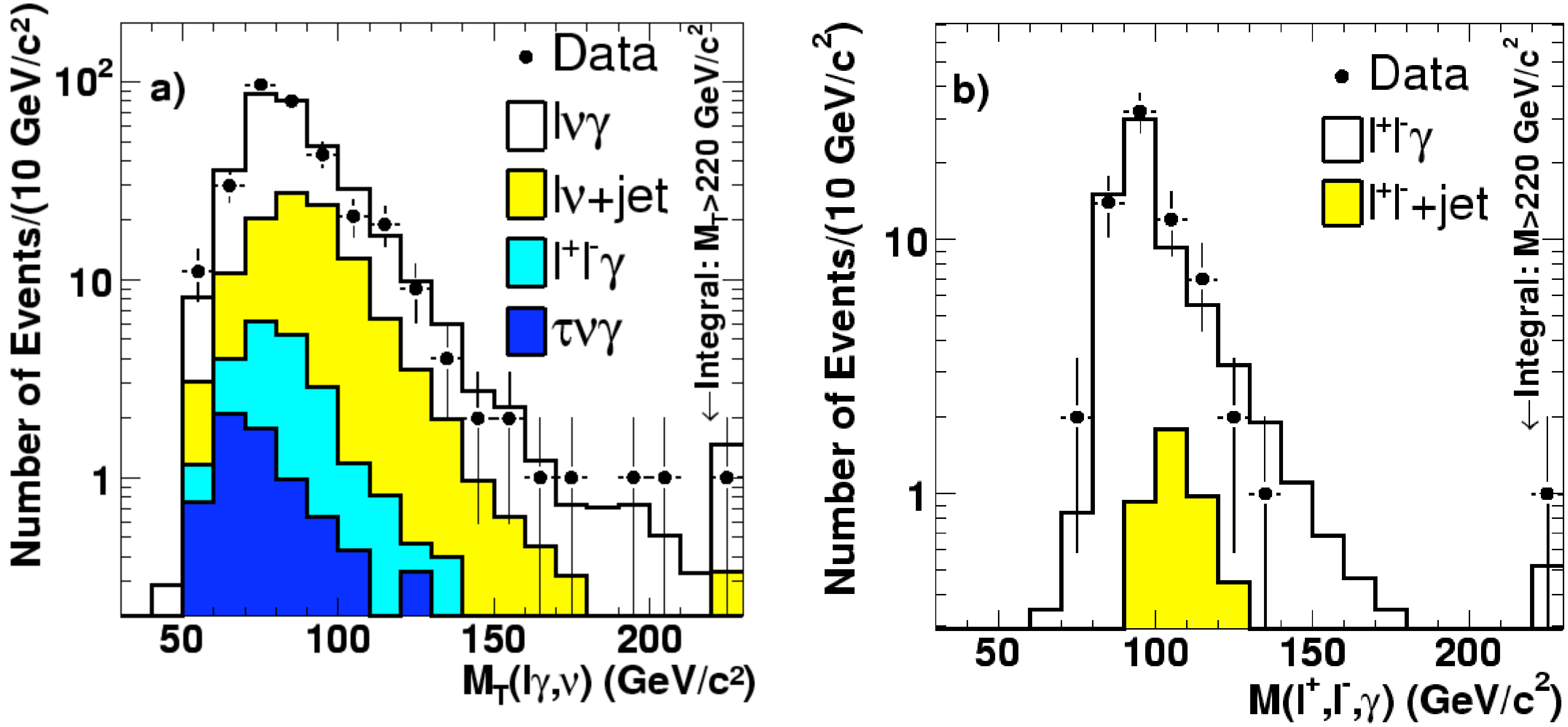
σ*BR ($Z\rightarrow\ell\ell$)=4.6 ± 0.6 pb
Theory: 4.5± 0.3 pb

PHOTON E_T



- Data agree well with SM
- Will be used to extract WWγ and ZZγ couplings

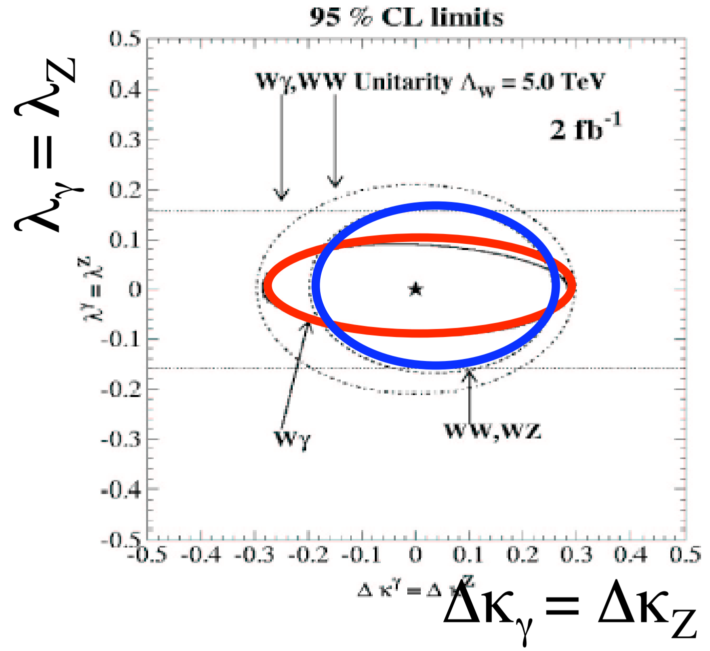
TRANSVERSE/INVARIANT MASS



- **Data agree well with prediction**
  - **no sign of any deviation at high mass**
- **Can be used to constrain e.g. W* and Z***

WWγ Couplings: Future

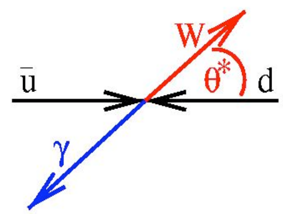
- **Tevatron constraints competitive with LEP with 2 fb^{-1}**
  - **Independent of assumptions on WWZ couplings**
- **LHC and LC will improve by 2 orders of magnitude:**
  - **Will probe with high precision:**
    - $\Delta\lambda/\lambda \approx$ **1/1000,** $\Delta\kappa/\kappa \approx$**3/100**

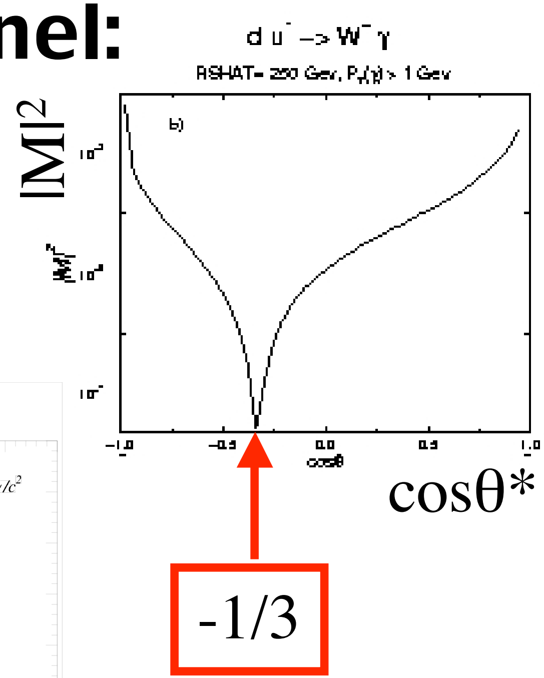


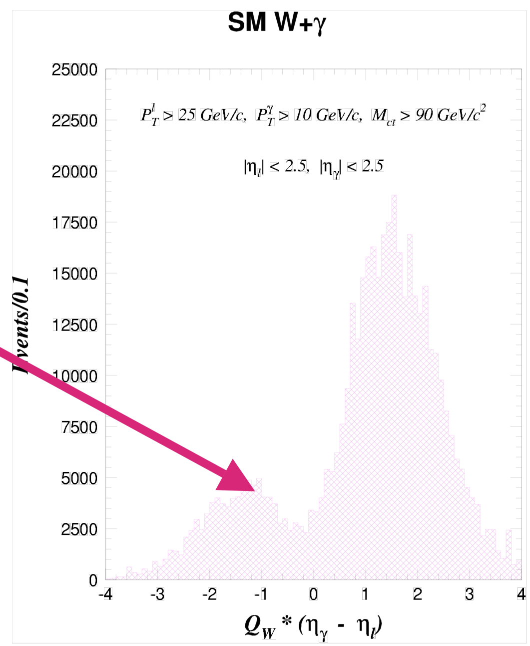
Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g_1^Z	0.0038	0.0024	0.0023	0.0007	0.0050

Radiation Amplitude Zero

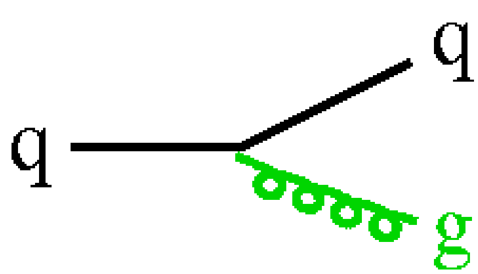
- "Radiation Amplitude Zero" due to interference of t-/u- and s-channel:
  - Suppressed: for W^- $\cos\theta^* = -(1+2Q_d) = -1/3$
  - Observable in angular separation of lepton and photon:
    - $Q_{lepton} \cdot (\eta_{lepton} - \eta_\gamma)$
  - Higher order QCD corrections spoil this:
    - At LHC invisible





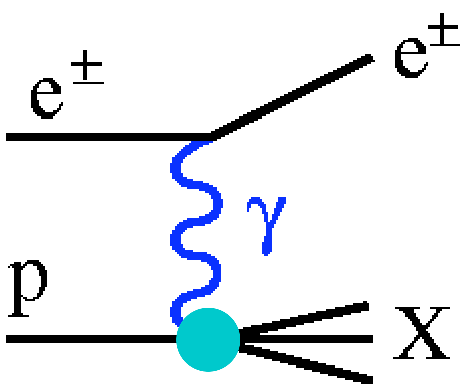


The Electroweak, the Strong and the Unknown



The Strong Force: QCD

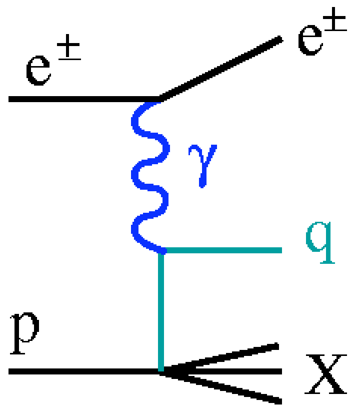
- calculations difficult since coupling, α_s, very large
  - high Q^2: asymptotic freedom (α_s <<1)
    - perturbative expansion can be made
- Measure proton structure function vs x and Q^2:
  - x = fractional proton momentum carried by parton
  - Q^2= momentum transfer
- Inclusive measurement probes
  - structure of proton:
    - x-dependence of parton densities not known a priori: must be determined from experiments
  - Perturbative QCD:
    - Q^2 dependence predicted by perturbative QCD: DGLAP evolution equations

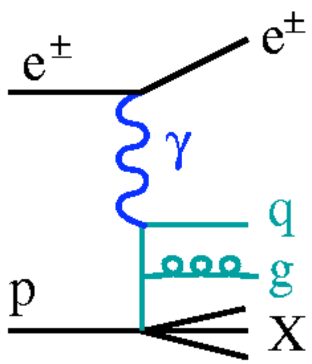


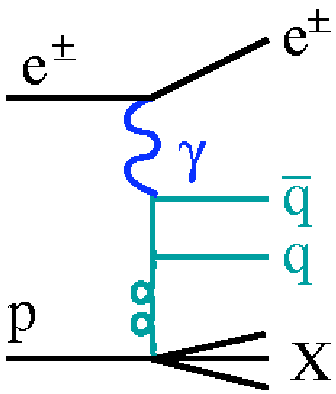
What happens there?

The Strong Force: QCD

- calculations difficult since coupling, α_s, very large
  - high Q^2: asymptotic freedom (α_s <<1)
    - perturbative expansion can be made
- Measure proton structure function vs x and Q^2:
  - x = fractional proton momentum carried by parton
  - Q^2= momentum transfer
- Inclusive measurement probes
  - structure of proton:
    - x-dependence of parton densities not known a priori: must be determined from experiments
  - Perturbative QCD:
    - Q^2 dependence predicted by perturbative QCD: DGLAP evolution equations



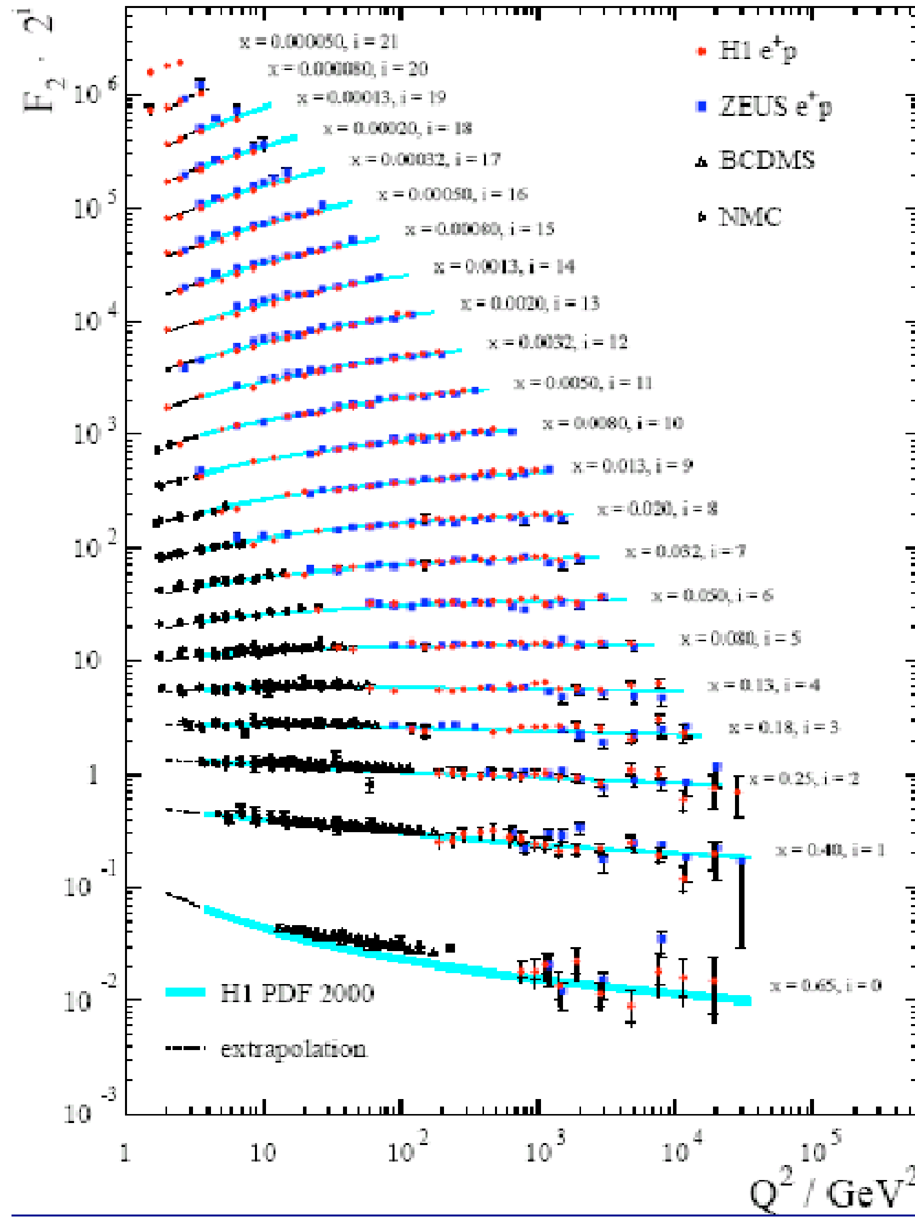




+ many more processes

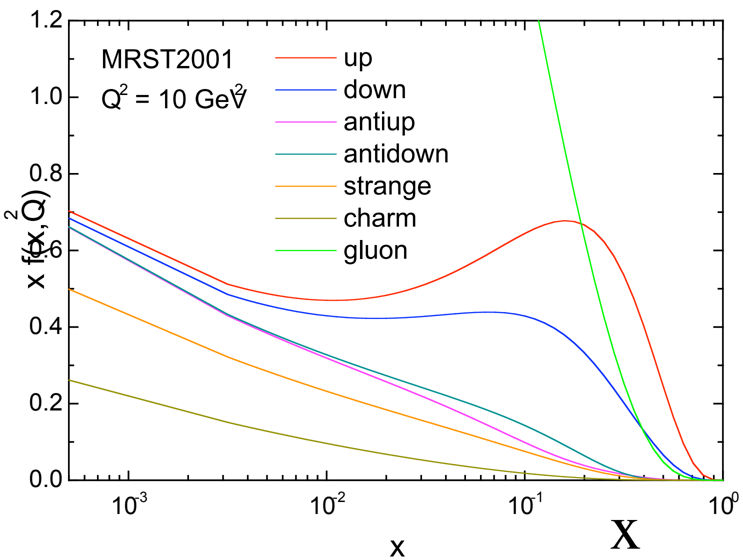
STRUCTURE FUNCTION

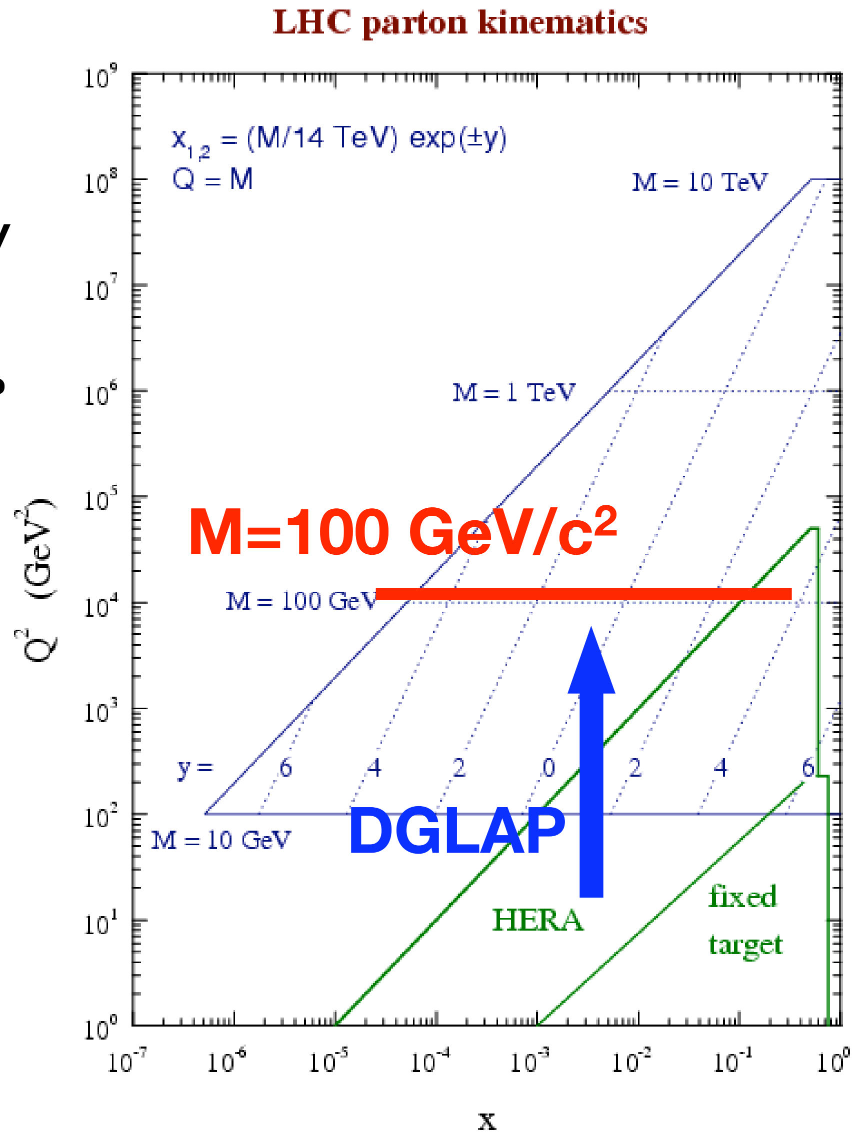
- **1969:**
  - **first measurement at SLAC**
  - **discovery of "scaling"**
  - **Partonic substructure of proton**
  - $\sigma \propto F_2\,(x,Q^2) \approx \sum e_q^{\,2}\, q(x,Q^2)$
- **HERA:**
  - **Vast increase in kinematic coverage**
    - **Increasing Q^2 = increasing resolution**
  - **Scaling violations**
  - **Good agreement with NLO QCD calculations**
  - **Precision about 2% per point**



IMPLICATIONS

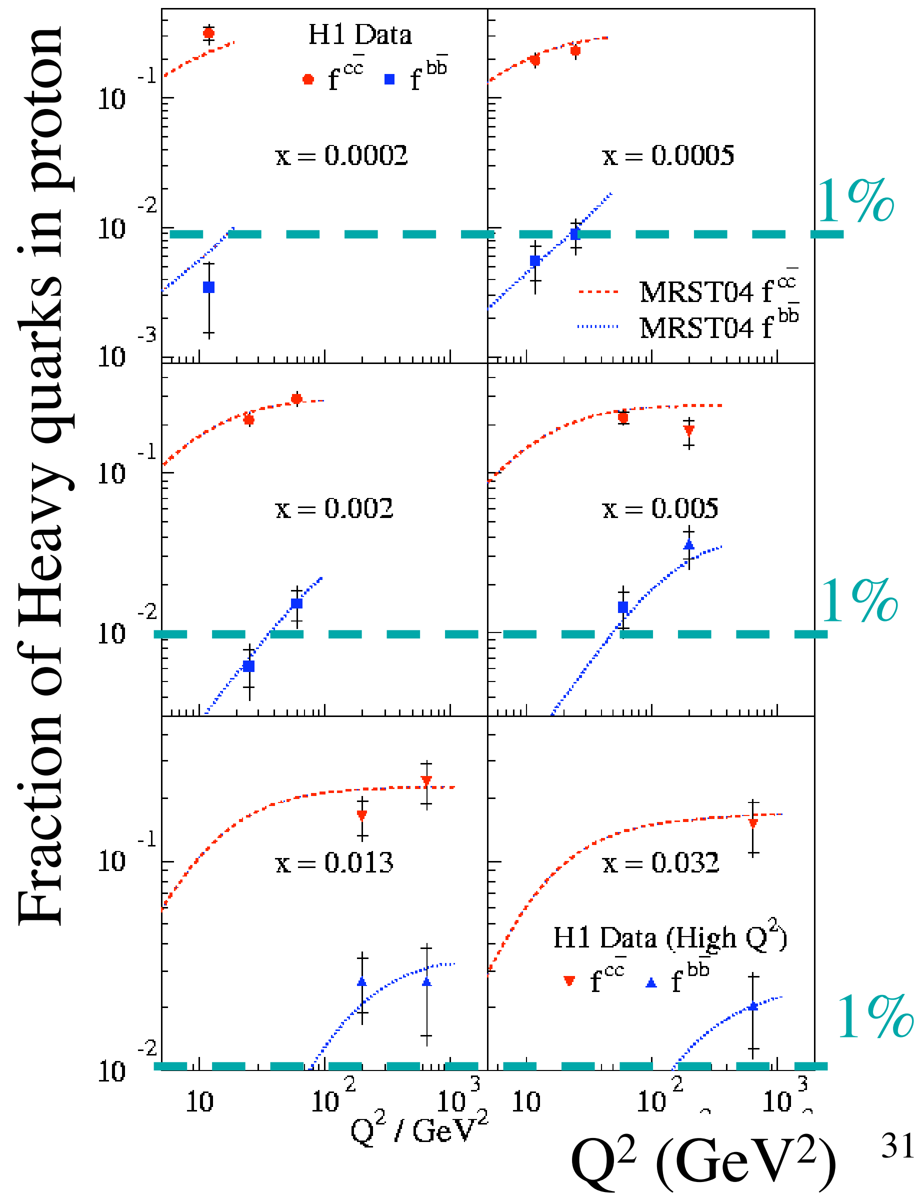
- **Important to know LHC cross sections,**
  - **e.g. Higgs is in x-range probed by HERA:**
    - **Current precision for gg -> H: 10%**
  - **All branching ratio and cross section measurements rely on knowledge of proton densities**





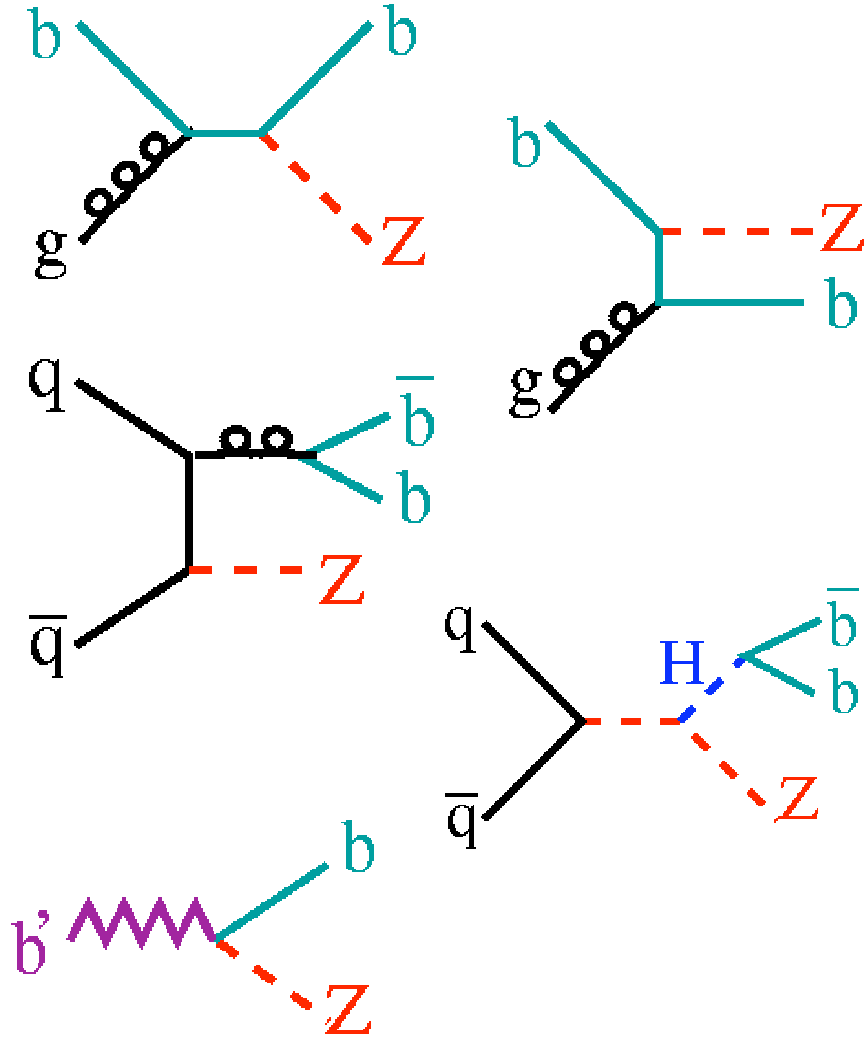
B-quark Density

- **Only 0.1–1% of the proton content:**
  - 10 times less than charm
- **Important for new physics processes:**
  - E.g. Higgs in SUSY may couple strongly to b-quarks (high tanβ)
- **test by measuring Z+b Production at the Tevatron:**
  - $Q^2 = m_Z^2 \approx 8{,}000\ \mathrm{GeV}^2$



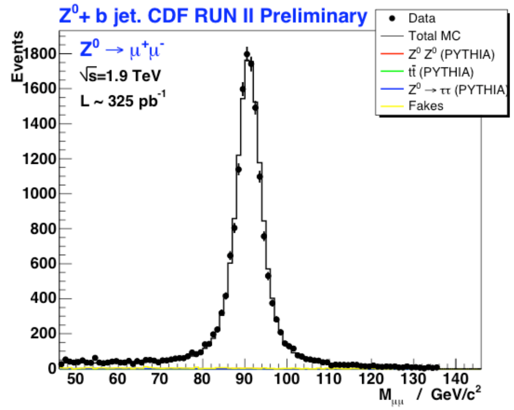
Z+B-JET PRODUCTION

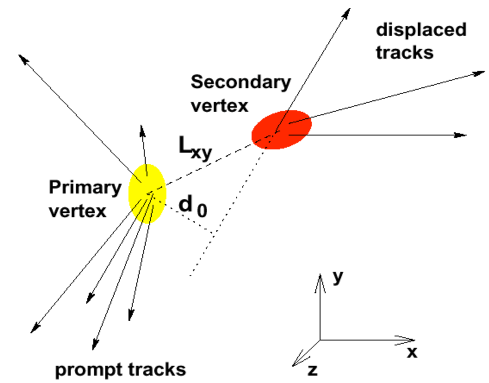
- Many possible production modes:
  - QCD:
    - Single b: ~ 0.6 pb
    - Double b: ~ 0.04 pb
  - New Particles:
    - Higgs boson
    - 4th generation quark: b'



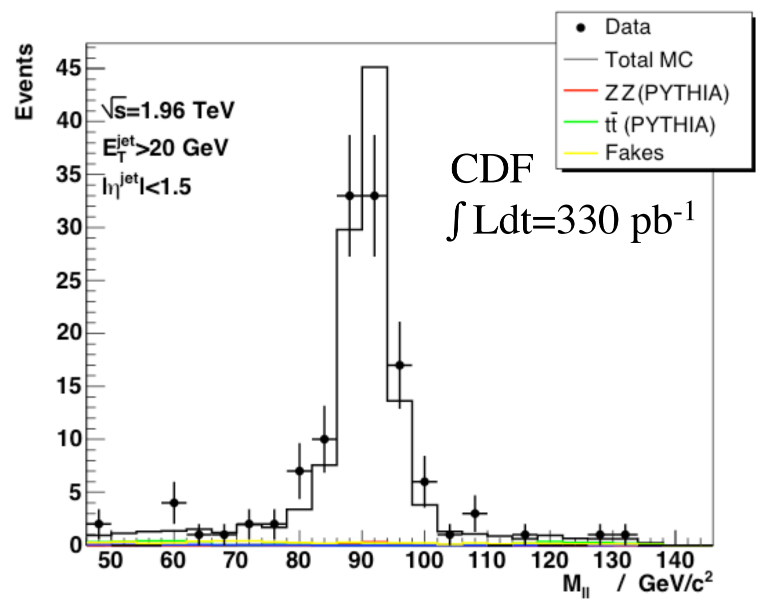
Measurement Technique

- Select Z bosons in electron and muon decay modes
- Identify b-quark through secondary decay vertex
  - Due to long lifetime of b hadrons
- 115 candidate events:
  - Background from non-Z production small:
    - 7.6 ± 2.5 % in e^+e^- mode
    - 3.9 ± 1.0 % in $\mu^+\mu^-$ mode



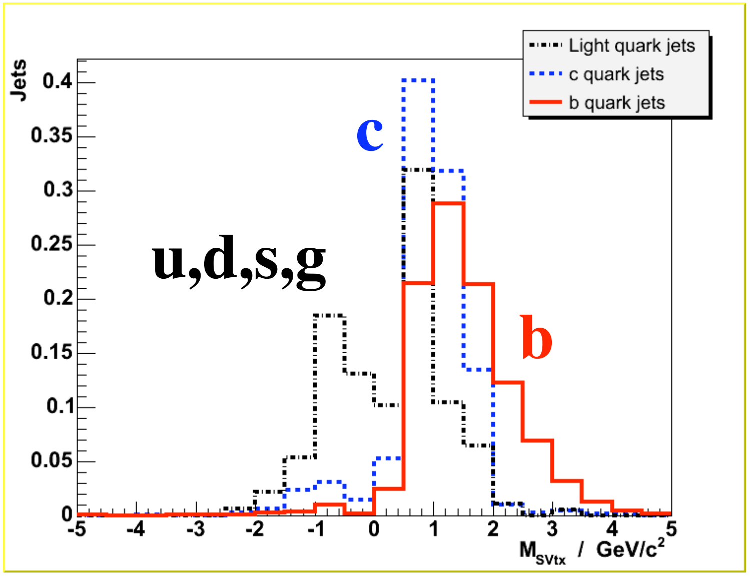


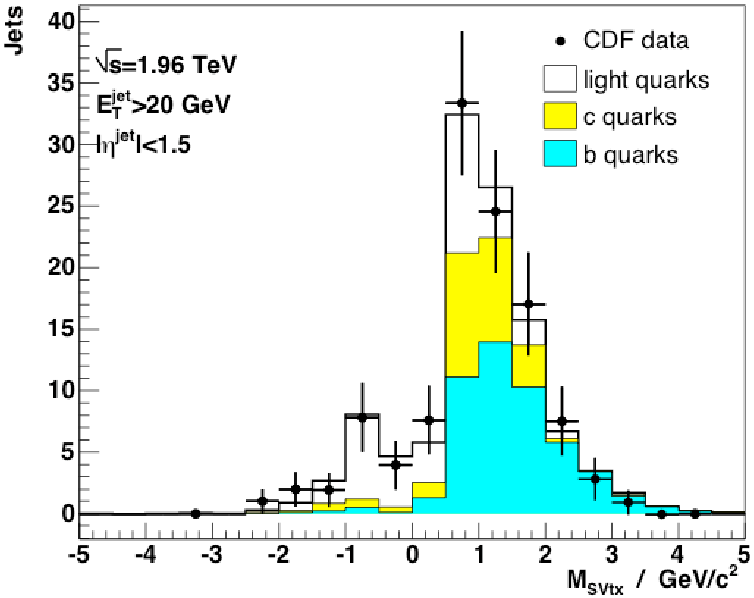
Z mass for events with b-jet



Separating b-Quarks

- $m_b > m_c > m_{u.d.s,gluon}$
- Reconstruct mass of tracks at secondary decay vertex:
  - Discrimination power
- Assign sign to mass:
  - Extra power to discriminate charm and light
- Fit templates to the data:
  - Good description of the data
- Use fitted number of events to extract cross section:
  - 49 ± 16 b-jets





Z+b-jet Cross Section

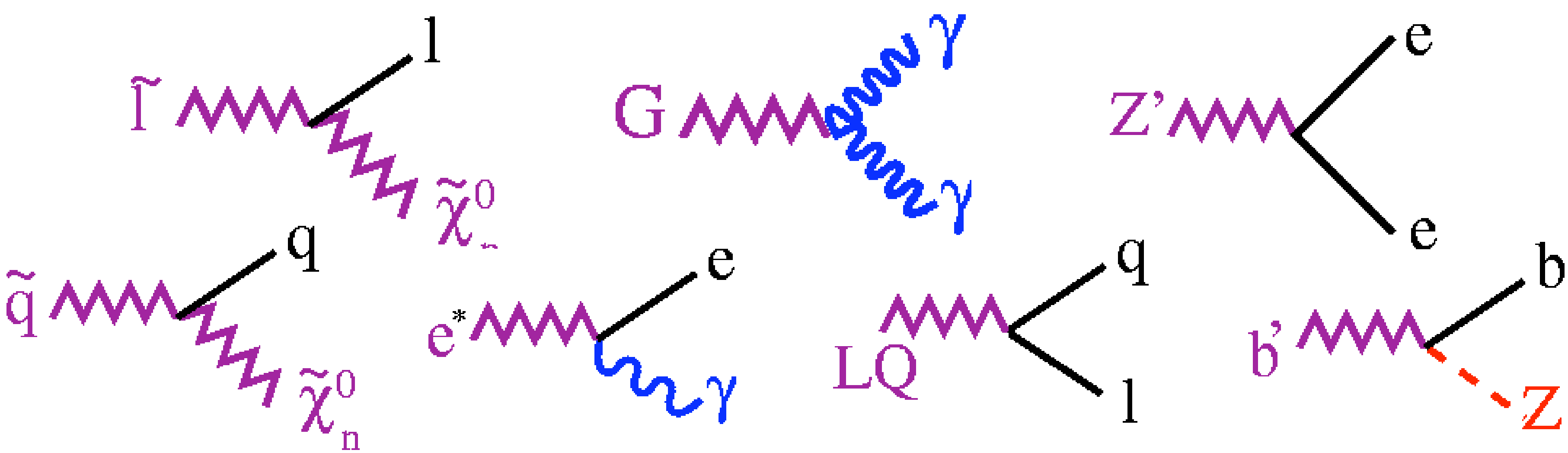
- **Extract *inclusive* jet cross section:**
  - Every b-jet enters the measurement
- **Measure also ratio of Z+b-jet to Z+any-jet production**

	Data	NLO QCD(*)	PYTHIA
σ(Z+b-jet) [pb]	0.96± 0.35	0.48 ± 0.07	–
σ(Z+b-jet)/ σ(Z+jet) [%]	2.4± 0.8	1.9 ± 0.3	2.1

- **Measurement agrees with NLO QCD calculations and PYTHIA but statistically limited:**
  - Expect improvements with
    - more data
    - improved b-quark tagging

(*) J. Campbell, K. Ellis

The Electroweak, the Strong and **the Unknown**

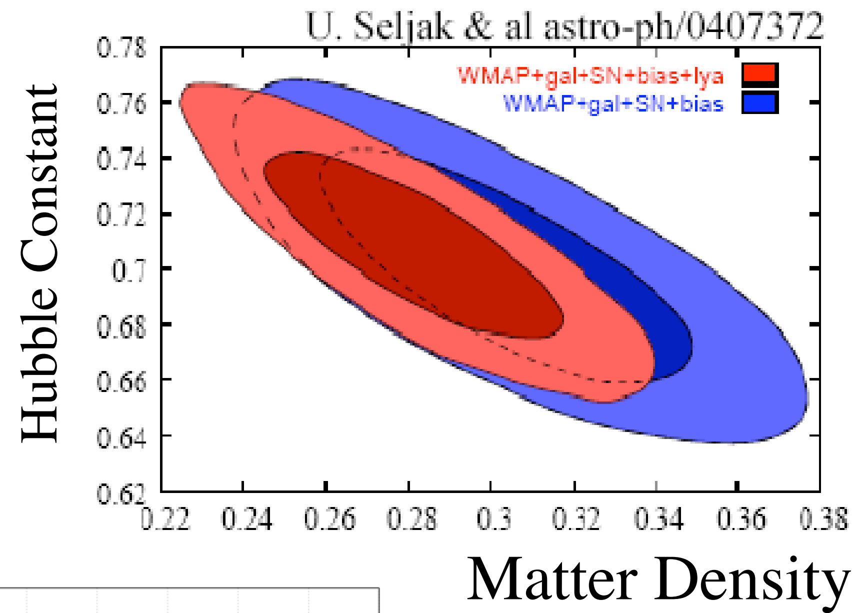


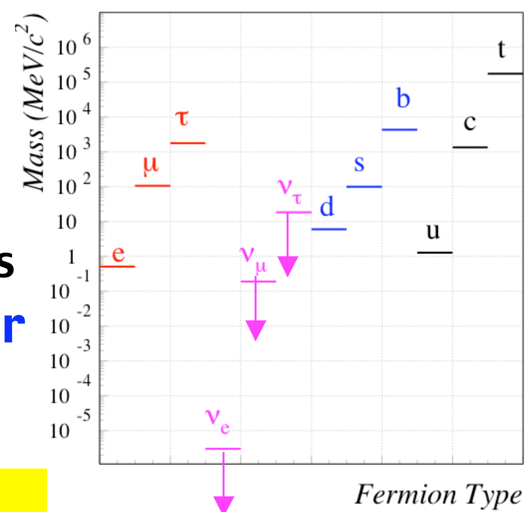
There is a Lot Unknown

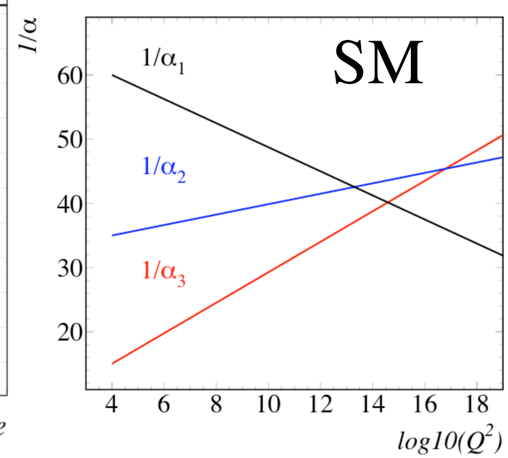
The Standard Model

- only accounts for **4% of matter** in Universe
  - No candidate for **Cold Dark Matter (~25%)**
- cannot explain large **mass hierarchy** in fermion sector:
  - >10 orders of magnitude
- does not allow **grand unification:**
  - electroweak and strong interactions do not unify
- has large radiative corrections in Higgs sector
  - require **fine-tuning** of parameters
- Cannot explain matter–**antimatter** asymmetry?

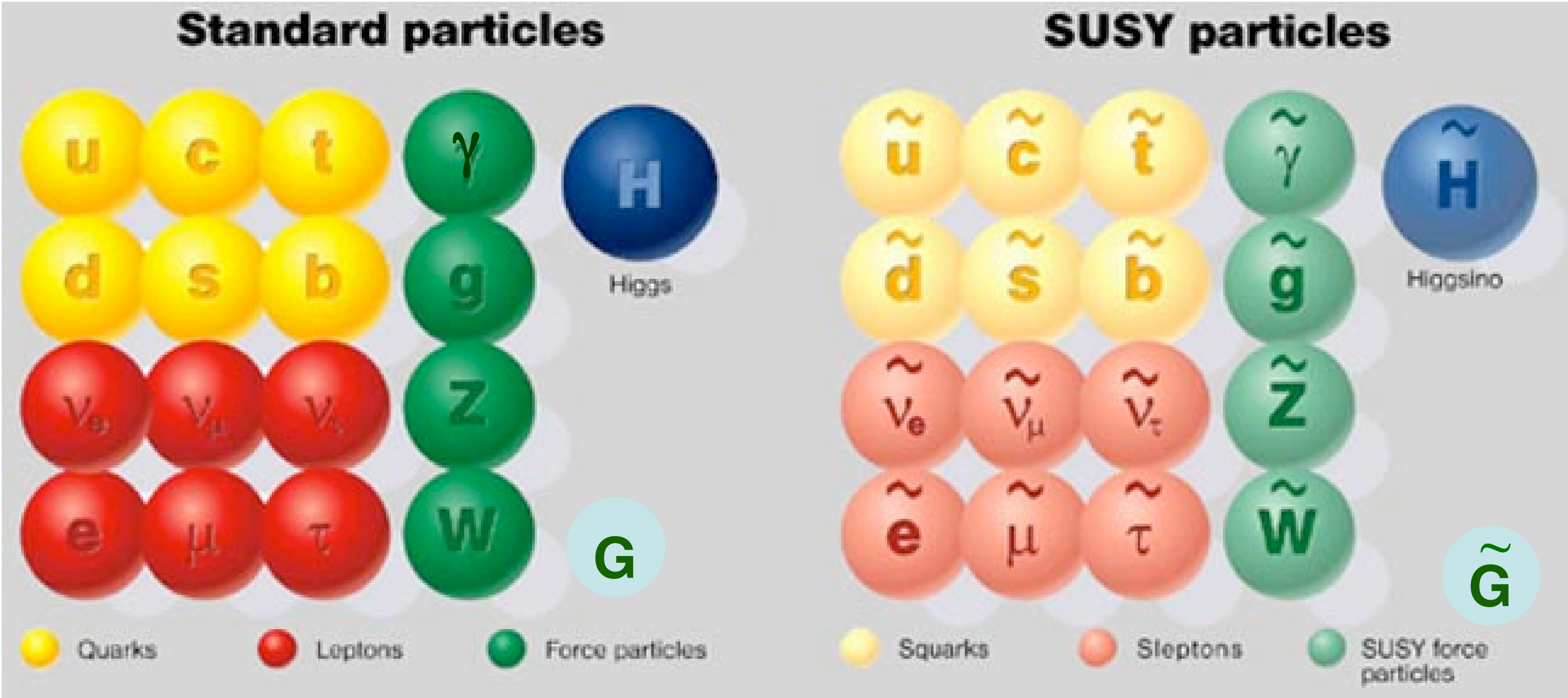
Supersymmetry can solve three of these problems







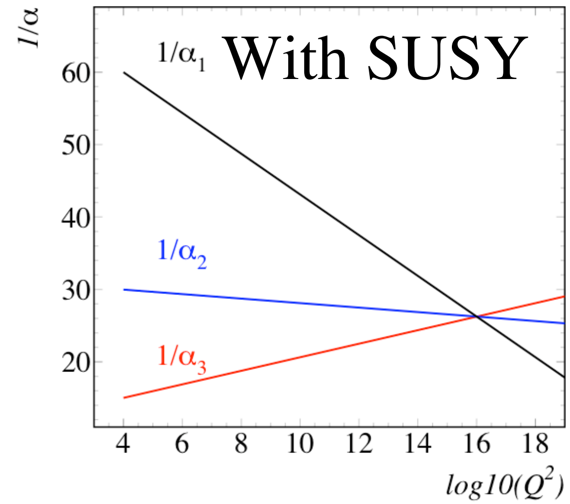
SUPERSYMMETRY

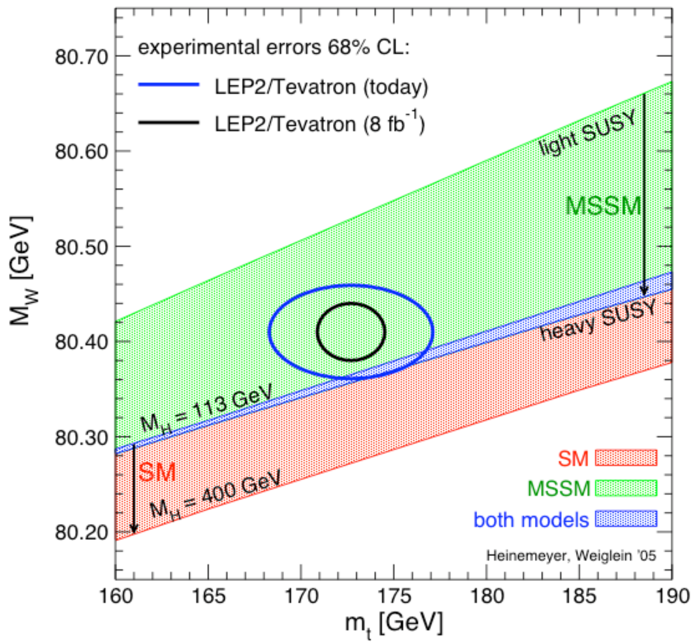


- SM particles habe supersymmetric partners:
  - Differ by 1/2 unit in spin
- No SUSY particles found as yet:
  - SUSY must be broken
  - breaking mechanism determines phenomenology

WHAT'S NICE ABOUT SUSY?

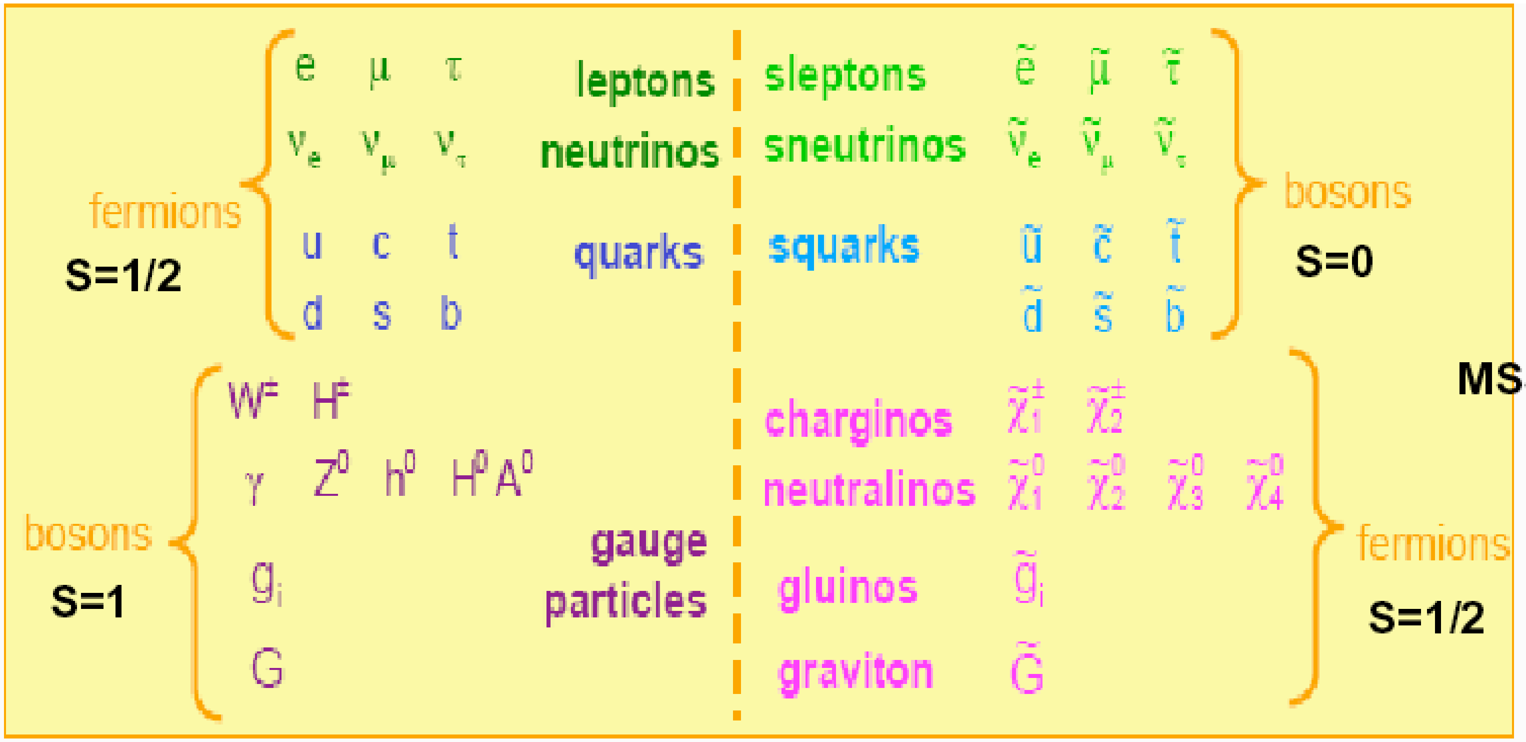
- Unifications of forces possible
- Dark matter candidate exists:
  - The lightest neutral gaugino
- Radiative corrections to Higgs acquire SUSY corrections:
  - No fine-tuning required
- Changes relationship between m_W, m_{top} and m_H:
  - Also consistent with precision measurements of M_W and m_{top}





Minimal Supersymmetric Standard Model (MSSM)

Particles R=1 R= $(-1)^{3B+L+2S}$ SParticles R=-1

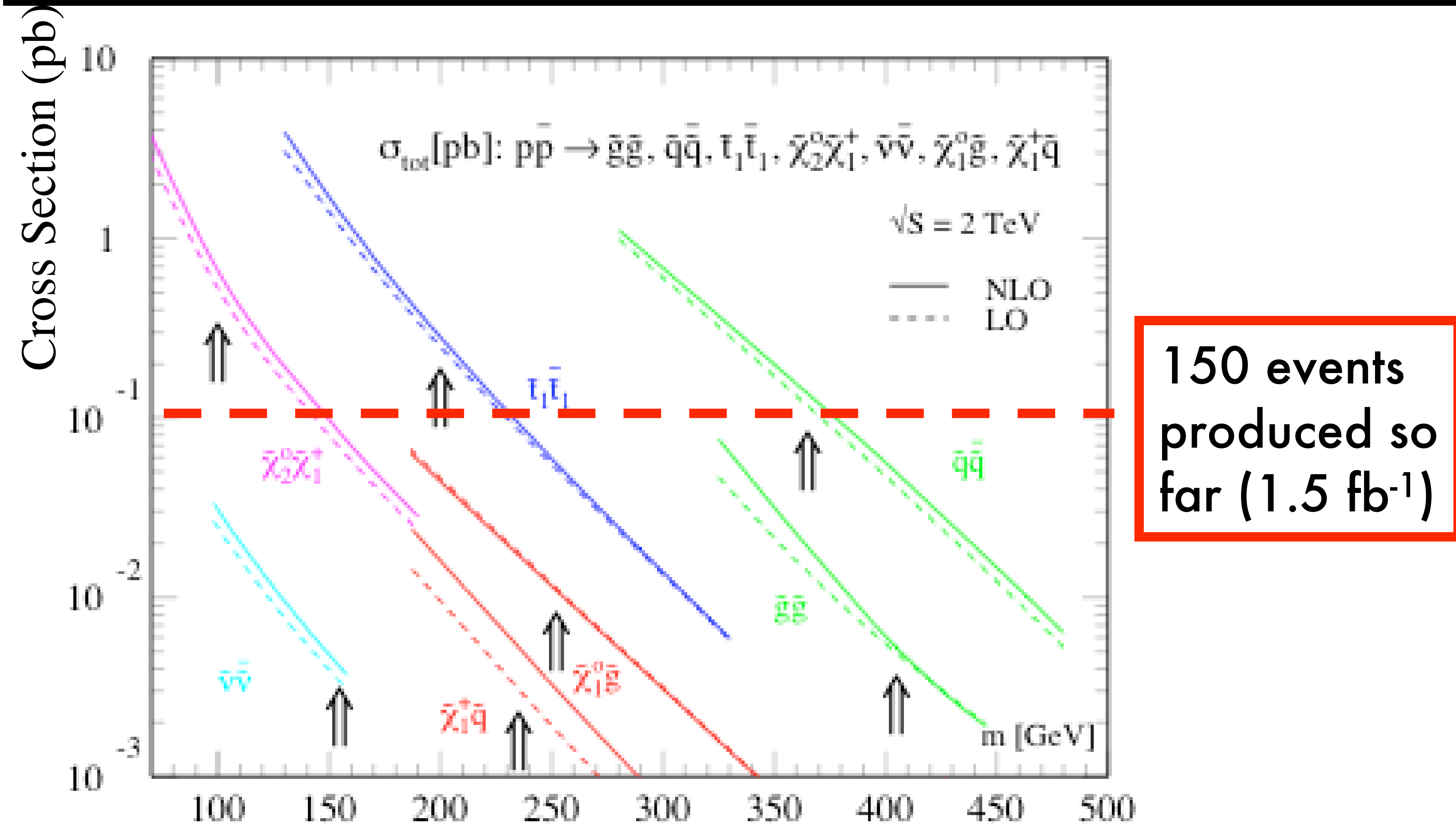


MSSM

MSSM has 124 parameters:
M_1,M_2, M_3, Gaugino masses, Sfermion masses
tanβ, μ, m_A Higgs(ino) mass/mixing
A_τ, A_b, A_t (+45 RPV)

- **SUSY is a broken symmetry**

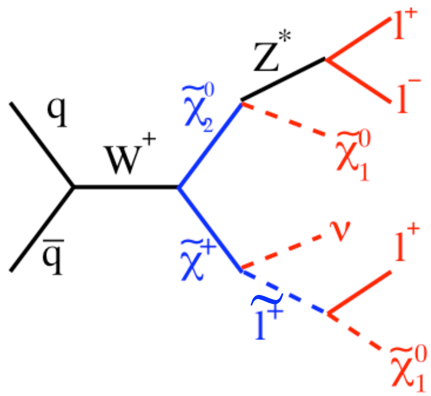
Sparticle Cross Sections: Tevatron

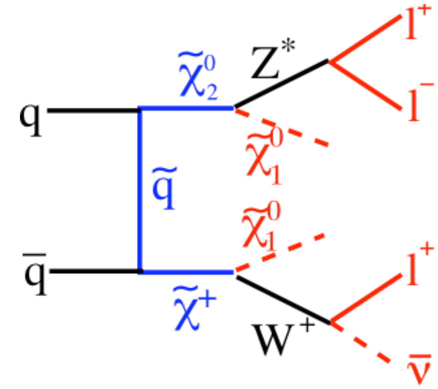


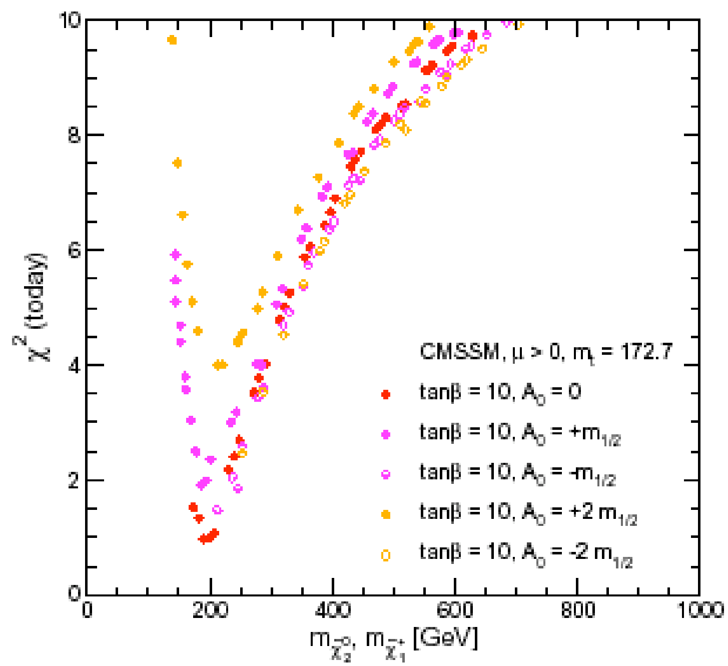
T. Plehn, PROSPINO

Charginos and Neutralinos

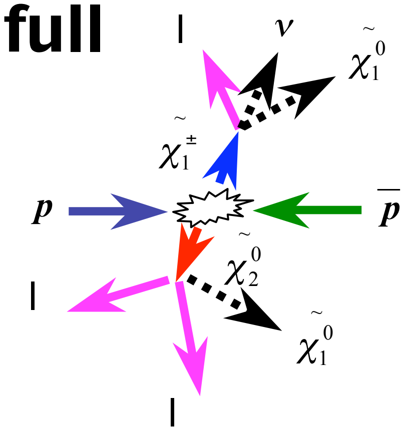
- **Charginos and Neutralinos:**
  - **SUSY partners of W, Z, photon and Higgs bosons**
  - **Mixed states of those**
- **Scenario here:**
  - **Neutralino LSP**
  - **3 leptons + $\not\!\!E_T$**
- **Recent analyses of EWK precision data:**
  - **J. Ellis, S. Heinemeyer, K. Olive, G. Weiglein:**
    - **hep-ph/0411216**
  - **Light SUSY preferred**

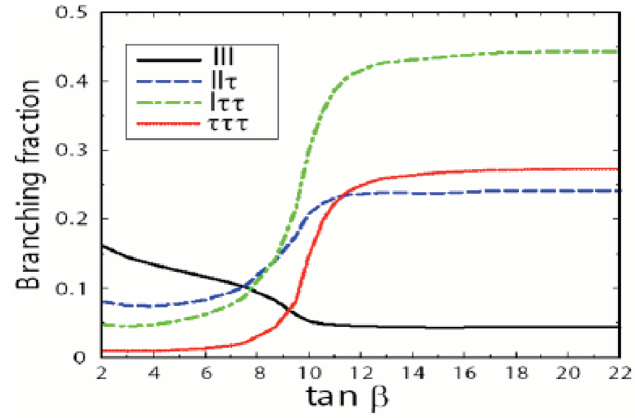




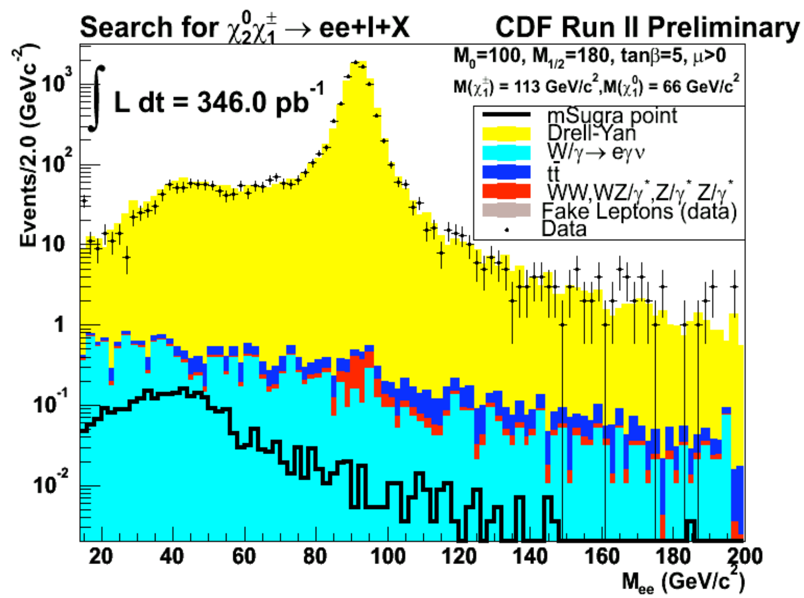


3 LEPTONS + $\not\!\!E_t$



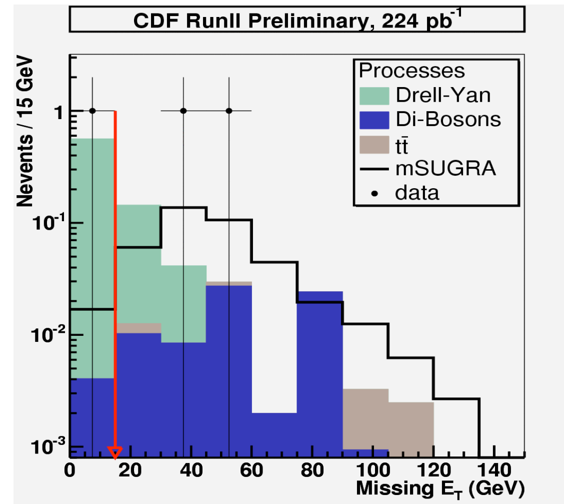


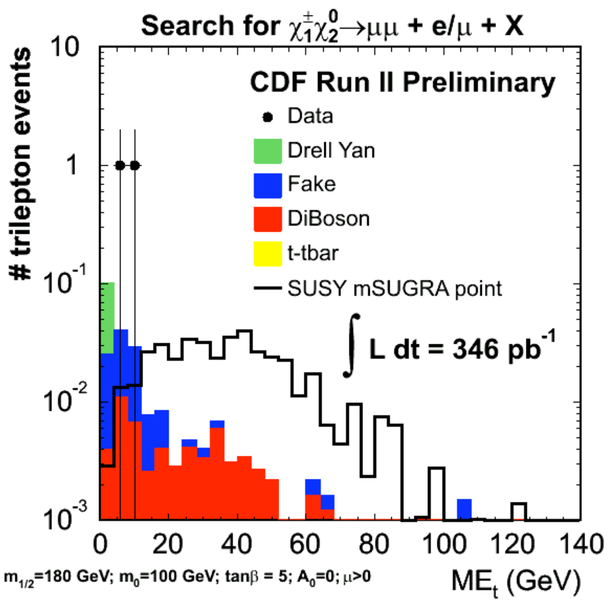
- Many analyses to cover full phase space:
  - Low tanβ:
    - 2e+e/μ or 2μ+e/μ
  - High tanβ:
    - 2e+isolated track
    - Sensitive to one-prong tau-decay
- Selection requirements:
  - Significant $\not\!\!E_t$
  - Dilepton mass >15 GeV/c^2 and not within Z mass range
  - Less than 2 jets

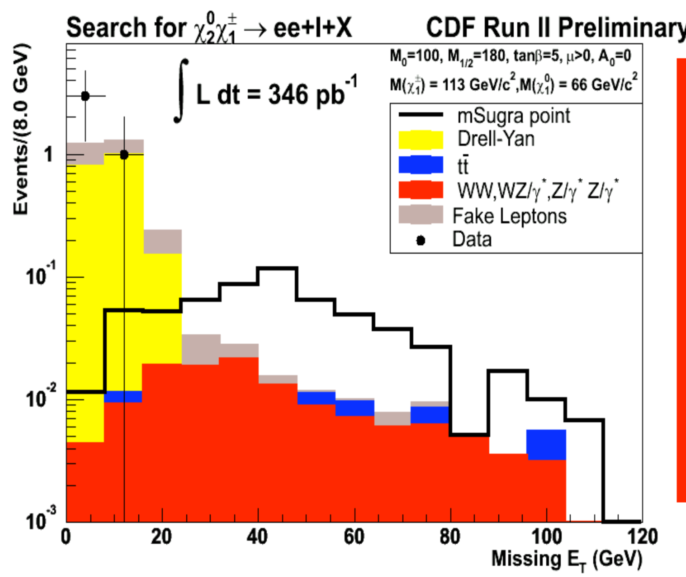


Trileptons: Result

Analysis	Total predicted background	Example SUSY Signal	Observed data
Trilepton (μμ+l)	0.09±0.03	0.37±0.05	0
Trilepton (ee+l)	0.17±0.05	0.49±0.06	0
Dielectron +track	0.48±0.07	0.36±0.27	2





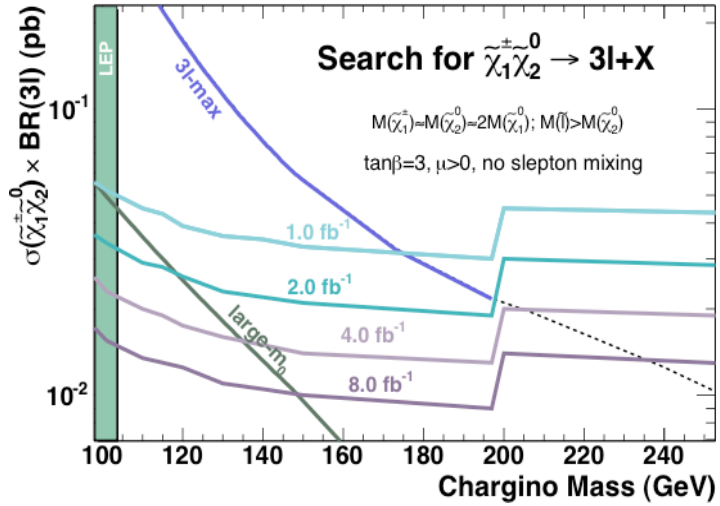


No hint of SUSY:

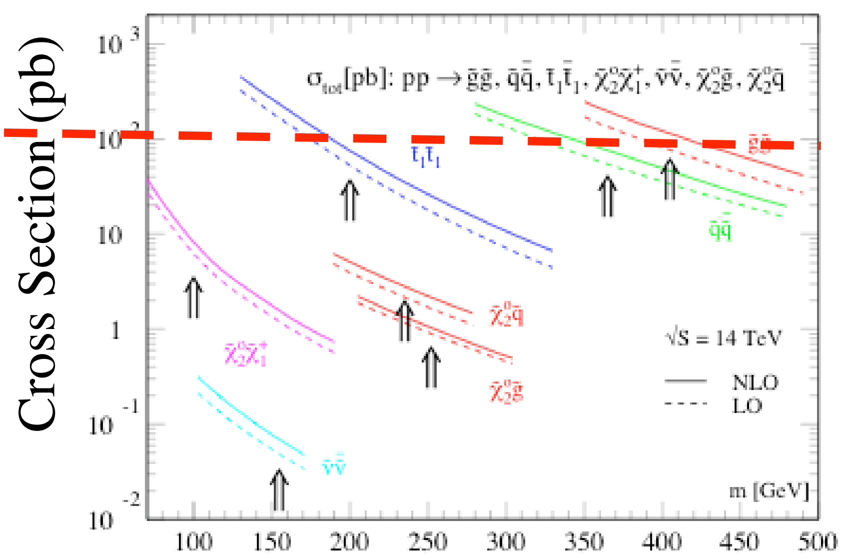
Inclusion of more data and interpretation in progress

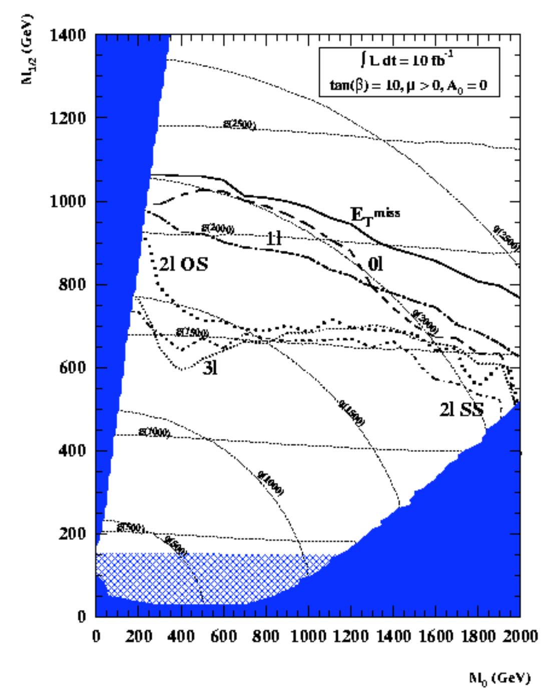
SUSY: Outlook

- **Trilepton search at Tevatron will probe:**
  - **Chargino masses up to 150–200 GeV/c²**
- **LHC will have excellent discovery potential!**



10,000 events with 1 fb^{-1}

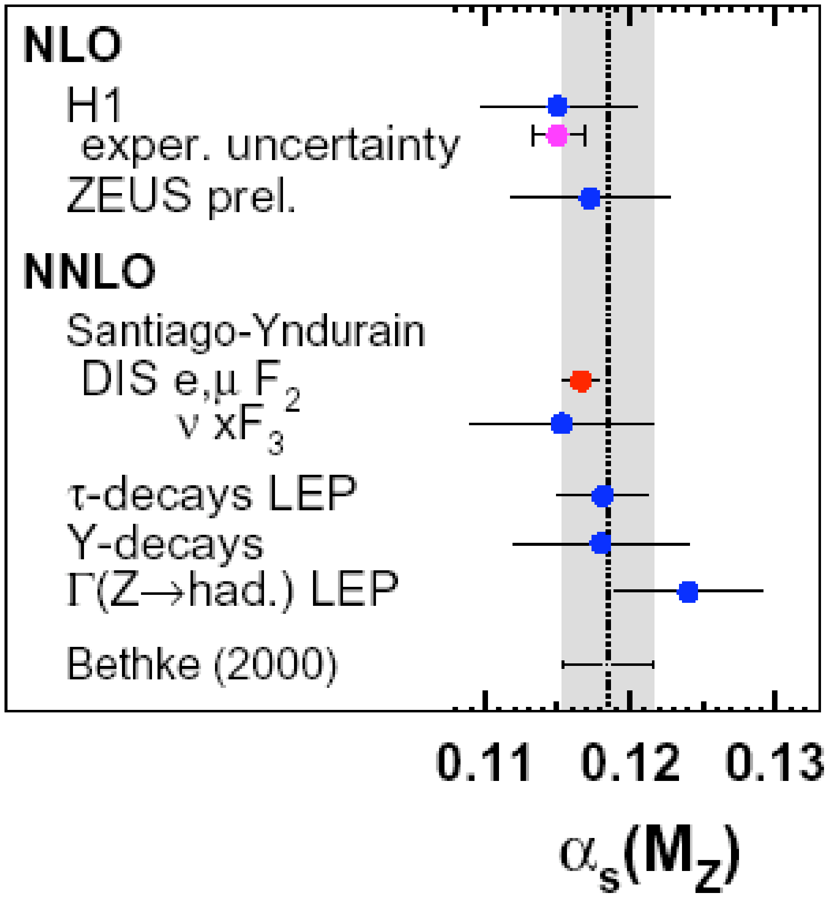




Conclusions and Outlook

- Precision tests of electroweak and strong sector of Standard Model
  - Critical aspects of electroweak and strong sector have been probed at high energy accelerators
    - so far the Standard Model survived all of them
    - we learned a lot from these tests
  - Will it survive new even higher precision in the next decade?
- Direct Searches for new unknown particles:
  - Many reasons for existence physics beyond the Standard Model
  - SUSY has attractive solutions to many problems
    - So far no sign of SUSY found but could appear any day
- Expect major progress in both areas in the next few years:
  - Tevatron (now) => LHC (>2007) => ILC (>2020?)

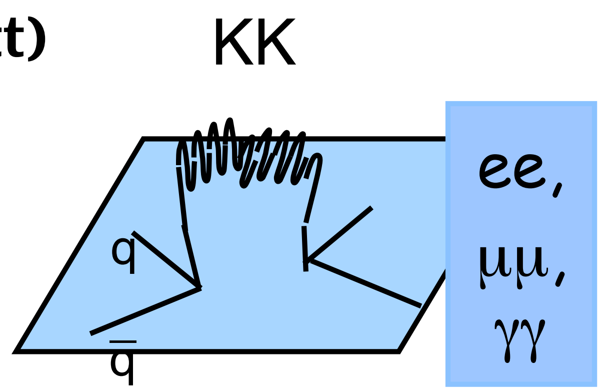
ALPHAS



NLO
H1
exper. uncertainty
ZEUS prel.
NNLO
Santiago-Yndurain
DIS e,μ F_2
ν xF_3
τ-decays LEP
Υ-decays
Γ(Z→had.) LEP
Bethke (2000)
0.11
0.12
0.13
$\alpha_s(M_Z)$

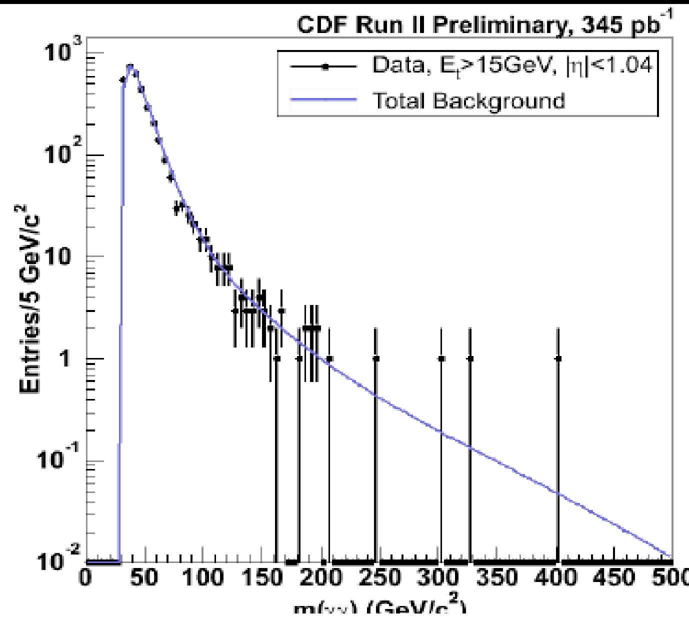
Extra Dimensions

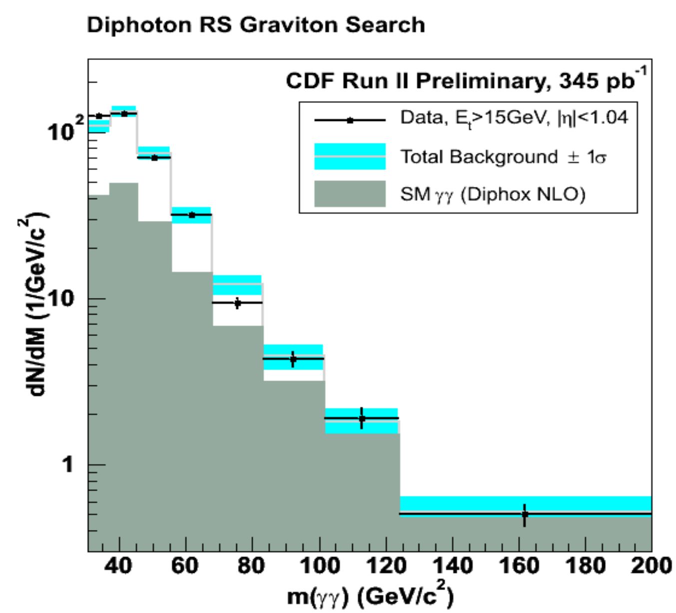
- Attempt to solve hierarchy problem by introducing extra dimensions at TeV scale
- ADD-model (Antoniadis, Dvali, Dimopoulos):
  - n ED's large: 100μm–1fm
  - $M^2_{PL} \sim R^n M_S^{n+2}$ (n=2–7)
  - Kaluza-Klein-tower of Gravitons $\Rightarrow$continuum
  - Interfere with SM diagrams: $\lambda=\pm 1$ (Hewett)
- Randall Sundrum:
  - Gravity propagates in single curved ED
  - ED small $1/M_{Pl}=10^{-35}$ m
  - Large spacing between KK-excitations
    $\Rightarrow$ resolve resonances
- Signatures at Tevatron:
  - Virtual exchange:
    - 2 leptons, photons, W's, Z's, etc.
    - BR(G->$\gamma\gamma$)=2xBR(G->ll)



Randall-Sundrum Graviton

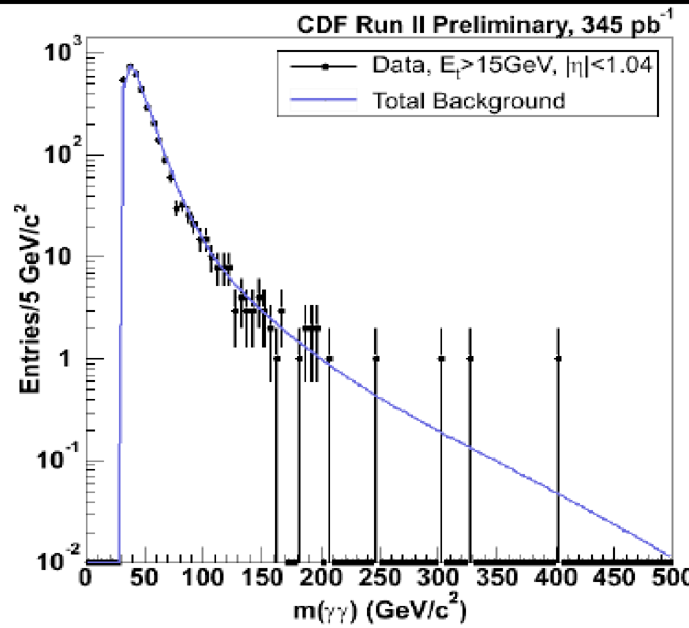
- **Analysis:**
  - 2 photon mass spectrum
  - Backgrounds:
    - direct diphoton production
    - Jets: $\pi^0 \to \gamma\gamma$
- **Data consistent with background**

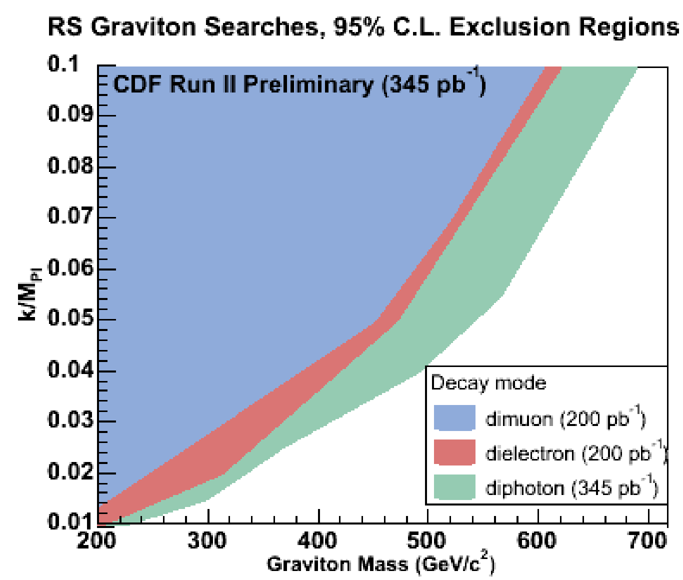




Randall–Sundrum Graviton

- **Analysis:**
  - 2 photon mass spectrum
  - Backgrounds:
    - direct diphoton production
    - Jets: $\pi^0 \rightarrow \gamma\gamma$
- **Data consistent with background**
- **Relevant parameters:**
  - Coupling: k/M_{Pl}
  - Mass of 1st KK–mode

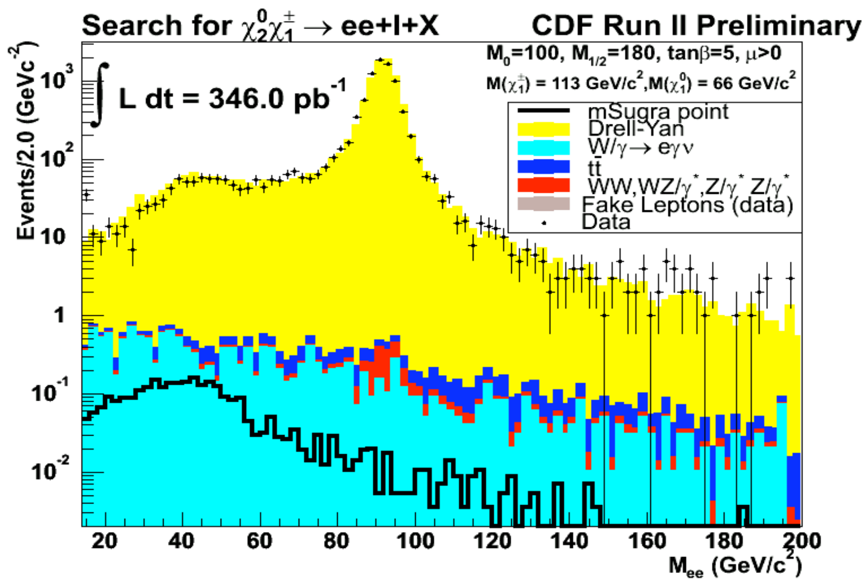


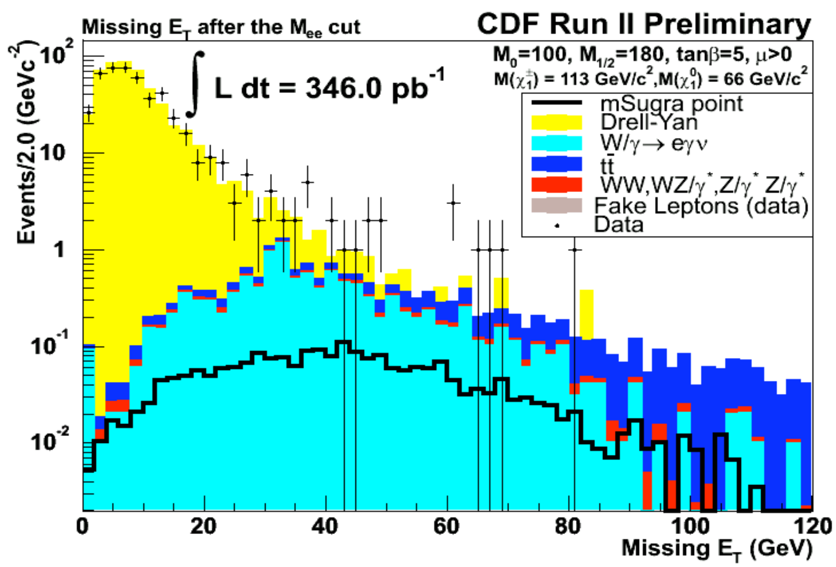


Trilepton Backgrounds

- Small signal:
  - Good control of backgrounds essential
- Main backgrounds:
  - Drell-Yan + fake lepton: 0.03
  - Drell-Yan + photon conversion: 0.07
  - WZ and ZZ: 0.07
  - Top: 0.01

*BG: for ee+lepton analysis

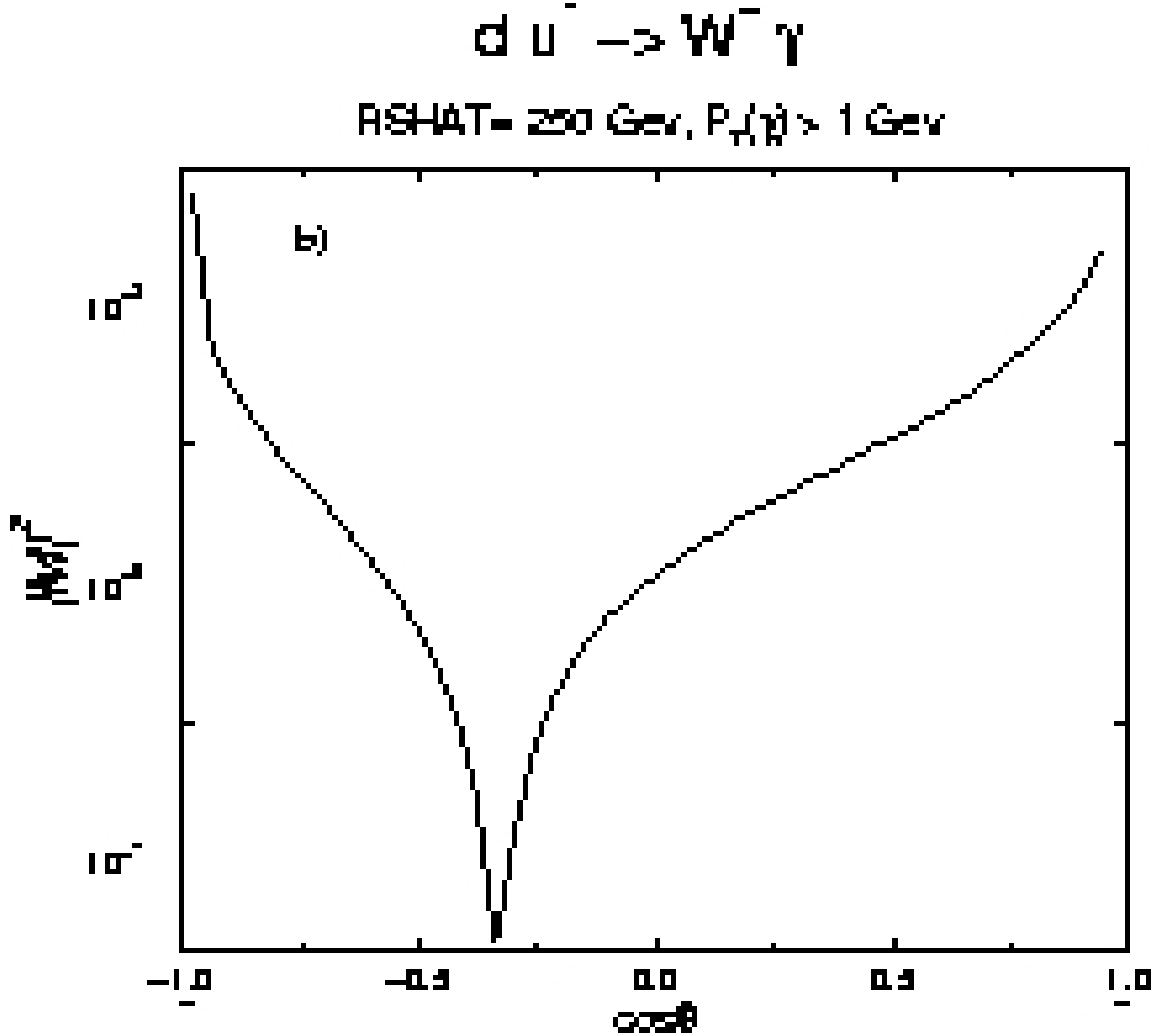




Conclusions

- blablabla

Radiation Amplitude Zero



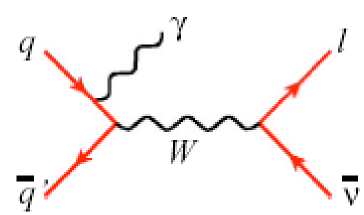
Ratio of Cross Sections

- Inclusive W and Z production:
  - Recent CDF result (hep-ex/0406078)
    - $\sigma(Z)$ / $\sigma(W)$ = **10.15±0.21%**
- Wγ and Zγ Production for $E_T(\gamma)$>7 GeV:
    - $\sigma(Z\gamma)$/ $\sigma(W\gamma)$ = 4.6/18.1 = **25+-5 %**

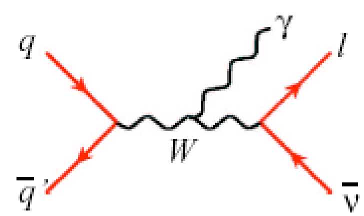
=> Expected due to

- Destructive interference of ISR and s-channel diagrams in Wγ
- No s-channel diagram in Zγ interference

=>Indirect Evidence for WWγ vertex!



ISR



WWγ